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STUDIES ON THE CLEANING OF FINE COAL BY A D.S.M. CYCLONE

T. E. MORIMOTO

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STUDIES ON THE CLEANING OF FINE COAL BY A D.S.M. CYCLONE

A DISSERTATION
SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

FACULTY OF ENGINEERING
DEPARTMENT OF CHEMICAL AND PETROLEUM ENGINEERING

by

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EDMONTON, ALBERTA,
APRIL, 1952

PREFACE AND ACKNOWLEDGMENTS

The investigations described in this thesis were conducted in the laboratories of the Research Council of Alberta, under the supervision of Mr. W. A. Lang, Senior Research Chemist. The work was carried out under the direction of a committee composed of Dr. G. W. Govier of the Department of Chemical Engineering of the University of Alberta, Dr. K. A. Clark of the Department of Mining and Metallurgy of the University of Alberta and Mr. W. A. Lang of the Research Council of Alberta. Sincere appreciation is extended to the members of the committee for their helpful advice and guidance during the course of this work.

The author also wishes to extend his sincere thanks to the many members of the staff of the Research Council of Alberta who have so generously given of their time and assistance.

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THE PROBLEM

The general problem was the cleaning of fine coal. Following a literature survey of coal-cleaning processes attention was centred on the D.S.M. cyclone washer. The problem was then divided into two phases. In the first phase the influence of various operating variables on the washing performance of the cyclone were to be investigated. In the second phase, the various means of judging coal-cleaning performance were to be studied to ascertain their behaviour when the specific gravity of separation was increased by varying the size of the cyclone underflow-opening and the specific gravity of the medium.

ABSTRACT

The general problem was the cleaning of fine coal. An extensive literature survey of coal-cleaning processes was made; following this, studies were begun on a three-inch D.S.M. cyclone washer. Experiments were performed in which fine bituminous coal (10- to 100-mesh) was mixed with a suspension of magnetite and water and pumped through the cyclone.

In the first phase of the investigation, the influence of the operating variables of pulp ratio of the feed slurry, specific gravity composition of the feed and particle size of the feed coal were studied. The cyclone was operated with a 0.78 square inch feed inlet area, 1.03 inch overflow diameter, 13.5 p.s.i.g. inlet feed pressure, 1.30 specific gravity medium and the size of the underflow opening adjusted to give ratios of underflow to overflow-opening area between 0.31 and 0.41. A pulp ratio of six-to-one was used for all of the experiments except those to determine the influence of pulp ratio.

Satisfactory cleaning was accomplished with a pulp ratio as low as four-to-one. A high error area of 86 and low Fraser-Yancey efficiency of 93.4% resulted with the three-to-one pulp ratio; with pulp ratios between four-to-one and eight-to-one, error areas ranging from 47 to 71 and Fraser-Yancey efficiencies 97.2 to 98.3% were obtained.

The amount of material within ± 0.10 specific gravity of the specific gravity of separation in the feed coal had no noticeable effect on washing effected by the cyclone. Error areas ranged from

29 to 46 and Fraser-Yancey efficiencies varied from 96.1 to 97.5% for feeds with ± 0.10 values between 23.6 and 9.8.

Particle size of the feed had a very marked influence on the cyclone cleaning results. Washing was performed at higher specific gravities of separation with less efficiency on the finer sizes. The specific gravity of separation was 1.63 and Error Area 44 for the 10- to 14-mesh fractions while these values were 1.84 and 84 respectively for the 65- to 100-mesh size fraction.

In the second phase of the investigation, the influence of size of cyclone underflow opening and specific gravity of the medium on the specific gravity of separation, Error Area, Probable Error, Fraser-Yancey Efficiency and Anderson Efficiency were studied.

It was shown that for washing performed by the cyclone the Error Area is not dependent upon the specific gravity of separation, which is itself dependent upon the cyclone underflow dimension and specific gravity of the medium. The Error Area, Probable Error, Fraser-Yancey Efficiency and Anderson Efficiency reacted differently when the cyclone dimensions and suspension specific gravity were varied. The Error Area and Probable Error gave similar results; the discrepancy between the two is likely due to the latter being an approximation of the former. The Fraser-Yancey and Anderson Efficiencies also gave similar results. However, the Error Area and Probable Error did not agree with the Fraser-Yancey and Anderson Efficiencies. The reason for this disagreement is due to the Fraser-Yancey Efficiency being a material balance on coal of a certain ash content whilst the Error Area and Probable Error show the sharpness of separation according to

specific gravity.

It was demonstrated that a probable error greater than 0.07 was not too great for satisfactory cleaning.

The "Magnitude of Imperfection" was shown to be meaningless for separations performed by the cyclone. The method of transformation of the distribution curves into straight lines proposed by Cerchar investigators was not satisfactory for the cyclone separations.

A new method of expressing the separation efficiency is proposed. This method is based upon the Error Area and expresses the Error Area as a percentage efficiency rather than as an area in square centimeters.

I INTRODUCTION

A major problem of the bituminous coal industry today is that of reducing the ash content of the finer sizes (minus $\frac{1}{4}$-inch of coal. This problem is particularly acute in Alberta where the coals have been rendered friable and bands of impurities have been intimately mixed with the clean material. These effects have been the result of tectonic movement, after deposition of the coal, in the mountain areas where the large deposits occur. As a consequence, most Alberta bituminous coals, as mined, contain a large proportion of fines and have a high ash content. In recent years, the advent of stripping operations and mechanized mining has further aggravated the situation. At the same time, the increasing competition from oil and natural gas is making it necessary for the coal operators to produce a cleaner coal.

Realizing the importance of this problem to the Alberta coal industry, the Research Council of Alberta agreed to undertake research in this field. However, before deciding on the particular process for cleaning fine coal that would be investigated, a detailed literature survey was made of all the processes used for cleaning both coarse and fine coal. A summary of the information gained in this survey has been included in the first section of this thesis. As a result of the survey an investigation was begun into the possibilities of the D.S.M. cyclone washer recently developed at the Dutch State Mines laboratories under M. G. Driessen.

II REVIEW OF COAL-CLEANING PROCESSES

Practically all of the processes for cleaning coal (with the exception of froth flotation) depend on the fact that particles of shale or of the higher-ash, so-called bone coal have a higher density than the particles of clean coal. In other words, all of the processes depend on the principles of gravity concentration for making a separation between clean coal and high-ash bone coal or shale. Methods of coal washing have closely followed the development of concentrating devices used for separating heavy minerals from their ores. However, because the difference in density between coal and shale is so much less than that between most heavy minerals and the gangue in their ores, cleaning coal is a more difficult proposition than that of concentrating heavy minerals.

Nevertheless, the cleaning of coal larger than $\frac{1}{4}$-inch is not too difficult. Jigs give reasonably efficient separations if they are properly operated and the coal is suitably sized before treatment. In recent years heavy-media washers have come to the fore because of the very sharp separations which they are able to make. However, the cleaning of fine coal presents a much more formidable task. Jigs and heavy media washers are inefficient when used on fine coal and dry pneumatic equipment generally has proven to be unsatisfactory, especially when the feed is damp. Wet concentrating tables are said to give fair results on coal as small as 60 mesh but require a very large floor space. At present, froth flotation appears to be the only method of satisfactorily cleaning coal finer than 60 mesh but it has the disadvantage of high cost.

There are two general classes of coal-cleaning methods. These are the wet processes and the dry pneumatic processes. The

equipment for the wet processes may be subdivided into jigs, heavy media, classifier-type and trough-type washers, and wet tables. The chief dry methods consist of the pneumatic table, pneumatic jig and air-sand processes.

WET PROCESSES

Nearly all of the coal that is wet-washed in Alberta at present is treated by means of jigs, although one mine is using heavy-media separation for coarse coal and wet tables for treating some of the fine coal. As far as can be determined these are the only wet processes in operation in the province at this date.

Jig Washers (8)

Jigging is the stratification of a mass of solid particles by upward and downward pulsations. The stratification is usually effected in a rectangular open-top container having a perforated bottom through which the pulsations of water are applied to the materials to be separated. The process of jigging usually involves three steps: (1) the reception of the raw coal, (2) the stratification of the coal and refuse so that the refuse settles to the screen plate, and (3) the overflow of the cleaned coal and the withdrawal of the refuse collected on the screen. Pulsations are imparted to the water in the washbox by means of piston plungers or compressed air. In the plunger type, a piston plunger is placed beside a fixed screen. As the water is forced down by the plunger on one side, it is forced up through the screen on the other. The Baum-type jig has a fixed screen with a sealed chamber over the space occupied by the plunger in the plunger-type jig. Compressed air is admitted to this sealed chamber which forces

the water downward on one side and upward through the screen on the other side. The air is then exhausted and the water again flows downward through the screen plate and upward in the air chamber so that the cycle may again be completed. The Vissac is an air-operated pulsator jig in which air is alternately compressed and allowed to expand to produce the pulsations. At present in Alberta nearly all of the wet cleaning of coal is accomplished with either Baum or Vissac jigs.

Coal-cleaning tests were made with a Baum-type and Vissac jig by Yancey and Geer (48)(49) of the United States Bureau of Mines in 1938. It is difficult to compare the performance of the two jigs on the basis of these tests because the feed sizes were not the same; the feed for the Baum jig was minus 3-inch coal whilst that for the Vissac was 3-to $1\frac{1}{4}$-inch and $1\frac{1}{4}$- to $\frac{1}{4}$-inch. There seemed to be little to choose between the cleaning accomplished on the 3- to $\frac{1}{4}$-inch range. Since coal smaller than $\frac{1}{4}$-inch was not cleaned in the Vissac jig no comparison of the performance of the two types of jig on minus $\frac{1}{4}$-inch coal can be made.

Heavy-Media Washers (38)

Heavy-media washers are sometimes called "float and sink" washers because they depend on the separation of heavy material from the clean coal by immersion of the raw feed in a heavy-medium bath; the higher ash material which has a density greater than that of the bath sinks, while the clean coal with a density less than that of the separating bath, floats.

There are several different types of heavy-media washers, each of which uses a particular suspension and bath design. Bath designs can be divided generally into two classes, deep and shallow tank types. The deep tank baths are based on the separation occurring in the central zone of a deep body of liquid, so that displacement effects are smoothed out in the large body of liquid available. The shallow tank processes depend upon a horizontal separation occurring progressively as the coal travels with the liquid along the tank. The distinguishing features of the two types, apart from actual size, are the flow conditions, and the methods of removing the refuse. The deep tanks are tapered downward from the separating zone to an outlet device (Chance and Cyanamid) or to an elevator boot (Barvoys and Tromp). These tanks are usually from 15 to 20 feet deep. The refuse has to settle through this depth of liquid and is usually then raised to discharge above the liquid level. The shallow type generally has a horizontal or inclined floor at the depth of separation (usually three to five feet). This floor may be traversed by a scraper as in the Dutch State Mines washer, or a rubber belt conveyor such as that used by the Ridley-Scholes process. With the Link-Belt washer the floor is a rotary drum. In the deep baths the tapering sides allow the refuse to be collected at the bottom of the tank at a central point. In the shallow-bath types the refuse settles on to the conveyor at any part of the floor area. There is thus a large area for deposition of the refuse which has only a short distance to sink.

Little current is needed to maintain a uniform specific gravity with a stable medium such as that used in the Barvoys process, although a slight upward current is employed to help movement of the lighter

coal and suspended middlings. On the other hand, in order to maintain the required specific gravity in the bath when using an unstable medium, the whole separating zone must be swept by current flow, either vertically as in the Chance, or horizontally as in the Tromp washer. Both stable and unstable suspensions are employed with the deep bath type of washer. Unstable suspensions cannot be used with the shallow tank types since the current flow, which is usually horizontal in washers of this class, does not prevent settling out of the suspension.

Deep Bath Types - The Chance process (32) uses a suspension of sand and water in a conical-shaped bath. The suspension is unstable due to the size of the sand particles (48 to 150 mesh) and so upward currents are necessary to keep the sand in suspension. This instability makes it rather difficult to attain a steady separating specific gravity with varying rates of feed and a large size range of feed coal particles. Medium recovery is fairly simple with this process due to the large grain size of the sand particles.

The Barvoys process (32) uses a mixture of barytes, clay and water for a suspension. An advantage of this process is that the medium is reasonably stable in the bath so that an accurate separation is accomplished. The high density of the barytes simplifies the operation and control of the medium, but it is a rather costly material. Emphasis in this process is placed on stability in the separating bath and almost "theoretical" results over a wide range of densities can be achieved. The average particle size (90% minus 270 mesh) of the solids in the medium is much smaller than it is in

the Chance washer.

The Tromp washer (7) is similar in principle to the Barvoys except for the middlings removal system and the material used as the suspension in the medium. In the Tromp process the middlings are removed by horizontal currents and an inclined scraper, whereas an upward current is utilized by the Barvoys washer. The Tromp system uses a finely-ground suspension of magnetite which is more stable than the coarse-sand medium of the Chance process but less stable than the barytes suspension of the Barvoys system. The equipment is designed to use the instability of the medium so that a low specific gravity layer exists at the top of the bath and a high specific gravity layer exists at the top of the bath and a high specific gravity layer at the bottom. Considerable circulation of heavy medium is required but less than if the system demanded the same specific gravity throughout the depth of the separator.

The American Cyanamid process (28) utilizes a cone similar to that employed in the Chance washer. Finely-ground magnetite (90% minus 325 mesh) in water is used as the medium and upward currents are not required to keep the magnetite in suspension. The coal floats on the surface of the bath and is removed by overflowing a weir. The refuse sinking through the medium is continuously removed from the bottom of the cone by an air-lift. Magnetic separators are used for recovery of the magnetite.

Shallow Bath Types - The Ridley-Scholes process (38), developed in England, uses a shallow bath of wedge shape with a rubber belt conveyor to remove the refuse from the floor of the bath. The

floating coal is discharged over a weir by paddles. The medium employed is mill-scale or iron ore which is rather coarse, being 80 to 90% through 200 mesh.

The Dutch State Mines washer is also a shallow bath type. It uses a suspension of loess in the water as the medium. Loess is a naturally occuring wind-blown material with a density of approximately 2.6 Horizontal currents are maintained by the motion of an endless scraper conveyor which removes refuse from the floor and clean coal from the surface of the bath.

The Link-Belt process (7) was developed in co-operation with the American Cyanamid Co. whose magnetic recovery system is used to recover the magnetite which is used as the suspension in this washer. The separatory vessel consists of a drum within which is a revolving, lifting wheel with perforated flights. The feed enters at one end of the drum and the clean coal is floated across the surface of the bath to an outlet weir. Refuse drops to the bottom of the drum, is picked up by the lifting wheel and is discharged on to an outlet launder at the top of the vessel.

Other Heavy Media Processes - The Lessing Washer (7) used a 1.35 specific gravity solution of calcium chloride in a cone-type separator and an upward current to maintain an effective specific gravity of about 1.5. The weak liquor washed off the coal was concentrated by heating it in a boiler and then passing it to a vacuum evaporator. The process gave very accurate separations and several plants of this type were built in England and Wales in 1928. They were abandoned after several years operation because of the high cost of the process.

The Belknap washer (7) employs a calcium chloride solution of a specific gravity much lower than the effective specific gravity which is maintained by mechanically induced upward currents. No attempt is made to remove all of the calcium chloride from the coal, so that a dustless, non-freezing product is obtained. It is stated that the size range that can be washed is limited to a four to one ratio between top and bottom sizes and three to one or two to one ratios are better. Several installations of this type of cleaner have been made in West Virginia and Virginia in the United States.

The Du Pont process (7) uses organic liquids of high specific gravity as the heavy medium. Halogenated hydrocarbons such as pentachlorethane and tetrabromoethane are used as heavy liquids either separately or mixed depending on the specific gravity desired. The coal is pretreated with a wetting agent which places a thin film of water over the surface of each particle prior to its introduction into the heavy liquid. This water film prevents absorption of the organic liquid by the coal during its passage through the separating tank. According to Mitchell (7) the losses of organic liquid run from five to nine ounces per ton of feed, amounting to from 3.1 to 5.6 cents per ton of feed coal. In 1936, the Du Pont Company built a pilot plant of 50 tons per hour capacity at Shenandoah, Pennsylvania, but as yet no commercial application of this process has been noted.

A new process of heavy medium cleaning is that of heavy-medium jigging (7). This method involves two essential features: (1) the circulation in the jig of a 1.7 to 2.0 specific gravity bone

middling which is 3/16 to 0 inches in size. This material fills the interstices of the jig bed and in effect converts the jig into a float and sink separator, and (2) the use of a suction stroke to hold the medium in the bed and prevent its washing over with the coal. It is claimed that this process effectively cleans coal with a size range of from 3 inch to 65 mesh. The difficulty of washing as shown by the ± 0.10 specific gravity distribution curve* is said to have no effect on the efficiency obtained.

Classifier Type of Coal Washers (28)

This type of washer depends on upward currents of water for making the separation. Some of the processes in use are the Menzies Hydroseparator, the Hydrotator and Hydrotator Classifier.

The Menzies Hydroseparator apparently gives rather poor separations, although it is claimed that this process is being utilized successfully by a major coal operator in the United States as a primary scalper to eliminate rock and thus do away with costly hand picking.

The Wilmot Hydrotator and Hydrotator Classifier are used in conjunction with one another, the former to clean coarse coal, and the latter to clean fine coal. The cleaning results with these two processes are said to be good but the feed coal must be carefully presized. For example, in one installation, with a size range of 1.3 inch to 28 mesh, the coal must be screened into six fractions which are then treated in four hydrotator and two hydrotator-classifier units.

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* See P. 84 for explanation of this curve.

The Sy-Vor Fine Coal cleaner (2) uses a fluidized bed with an upward current of water to separate shale from the coal. A slight pulsating action is employed to assist in the sorting of coal from refuse. Work so far has been done only on a laboratory scale and no commercial utilization of this process has as yet been noted.

Trough or Launder Washers (37)

In the launder process, a stream of liquid carries the material to be separated down a channel provided with draws for separating the heavy-gravity product and some means for overflowing a lighter one. A comparatively solid bed of material forms on the bottom of a launder, while above this bed is found a layer of particles moving at a slow speed. Above this layer, successive strata move with greater and greater velocity. Hindered settling conditions prevail in this flowing mass of material and govern the fall of particles to the bottom. In hindered settling, particles settle in the following order:

1. Large heavy particles.
2. Large light particles and small heavy ones.
3. Small light particles.

If the launder is operated so that only the first two reach the bottom, then the selective effect of the flowing stream is effective in transporting lighter material faster and consequently farther down the launder. These particles are then subjected to removal in the following order:

1. Large light particles.
2. Large heavy particles.
3. Small heavy particles.

If this process could be stopped with the removal of large light particles, the separation would be a perfect one. However, this is not possible because of turbulence in the flowing streams, the entrapment of light particles by the bed, and the lessening of the density of the bed by the withdrawal of products.

The most common launder washer is known as the Rheolaveur. Shallow pockets are spaced at points along the bottom of the trough for the removal of heavy particles against rising currents of water. In some cases the feed coal is not presized and minus 4-inch coal is fed to a coarse coal rheolaveur unit. The minus 3/8-inch coal is screened out and rewashed in a fine coal rheolaveur unit. According to Needham (34) trough washers give results similar to those given by jig washers, i.e. fair cleaning for coal larger than 30 mesh, and negligible cleaning for coal smaller than this.

The Lamex is a trough or launder-type washer which was developed in France by the Societe Lamex. The inclined trough has a varying cross-section; at the upper end the cross-section is rectangular in shape and gradually changes to a rounded U-shape, until at the bottom end, the cross-section is a sharp V. The performance of this washer is said to be greatly influenced by the shape of the trough. A splitter at the end of the trough divides the coal into three products: clean coal, middlings, and refuse.

An experimental Lamex washer has been installed at Blairmore by West Canadian Collieries, who claim to have obtained good cleaning results with it. Latest reports indicate that a series of Lamex washers are to be installed by this company for washing fine coal.

Wet Concentrating Tables

The wet concentrating table (11) consists of a sloping deck with longitudinal riffles. The feed, consisting of a water and coal mixture, is fed to the upper side of the table and water is introduced parallel to the feed. A differential motion is imparted to the table which makes it approach its reversing point and recede from it with greater speed at one end of its travel than at the other.

The most generally accepted explanation of the action of the Concentrating Table is that as the coal is fanned out over the table deck by the differential motion and gravitational flow, the particles have become stratified in layers behind the riffles. This stratification is followed by the removal of successive layers from the top downward by cross-flowing water as the stratified bed travels toward the outer end of the table. The cross-flowing water is made up partly of water introduced with the feed and partly of wash water fed separately through troughs along the upperside of the table. The progressive removal of material from the top toward the bottom of the bed is the result of the taper of the table riffles toward their outer end, which allows successively deeper layers of material to be carried away by the cross-flowing water as the outer end of the table is approached. By the time the end of the table is reached only a thin layer, probably not thicker than one or two particles, remains on the surface of the deck, this being finally discharged over the end of the table.

Although the fundamental principle of the wet table is that stratification is due to the nearly horizontal action of the table deck and the cross-flow of water, it is thought by Gandrud (23) that some

hindered settling occurs in the vicinity of the riffles. While the effect of hindered settling along any individual riffle is probably relatively small, the cumulative effect along the entire series of riffles across the width of the deck may be large enough to have a material influence on the character of the table separation.

According to Gandrud (23), tables have a high cleaning efficiency on the sizes between 1/4-inch and 65-mesh, while the cleaning on minus 100-mesh material is practically zero. At present, the table is one of the most efficient devices for cleaning fine coal below 1/4-inch in size. An advantage of this process is that no suspension medium, with its attendant recovery problems, is required. The main disadvantage is the large floor space needed, e.g. a table handling five to seven tons of coal per hour requires an area of approximately 200 square feet.

At present, as far as can be ascertained, wet tables are used in only one coal cleaning plant in Alberta. This is at the Greenhill tipple of West Canadian Collieries at Blairmore, where four Deisster tables have been installed.

Humphreys Spiral

The Humphreys Spiral (26) consists of a spiral channel of modified semicircular cross-section. A typical installation for treating fine coal consists of six full turns in a vertical height of five feet with an outside diameter of two feet. A circular refuse port is provided at each 120° interval of spiral turn at the lowest point in the cross-section of the channel. A small launder paralleling the main channel carries wash water, which is introduced as a cross-flow at the inner

edge of the stream below each refuse port. Coal and water at a solids concentration of 15 to 20% is introduced at the top of the spiral. As the coal flows downward it is stratified in the stream according to particle size and specific gravity.

The following explanation of how the spiral works is given by Gleeson (27):

> "As water flows down the spiral channel of modified semi-circular section, each element will be subjected to a centrifugal force, tangential* to the channel, directly proportional to the square of the velocity of flow and inversely proportional to the radius at which the element is located. This centrifugal force piles water up on the outer run of the spiral until the flowing stream reaches an equilibrium between centrifugal force outward and gravitational force downward. Once established, the position of the stream is fairly constant for uniform pitch and radius.
>
> "Velocity of the spiral stream decreases with depth from its maximum just below the water surface until it approaches zero velocity at contact with the channel. The largest percentage decrease in velocity will occur nearest to the channel contact, giving rise to the fluid film concept that is well-developed in hydrodynamic literature.
>
> "In any curved channel, whether a pipe or a river bed, the bottom layer of water, retarded by friction has much less centrifugal force and consequently will flow sidewise along the bottom toward the inner bank of the curved channel, carrying with it the heavier particles of sand. Simultaneously with this bottom flow of water inward, the upper mass of water must flow outward to replace it. There is, consequently, besides the flow of water down the length of the spiral, a flow of decreasing velocity downward and across the channel to the inside, then upward and across the channel to the top, progressively increasing in velocity until friction again enters.
>
> "The several flows and forces combine to sort and concentrate any particles which may be suspended in the stream. Oddly enough, a limited size classification also takes place. Particle size, within limits, is not a critical factor, and no particular advantage is gained by prior classification. Once the idealized arrangement has been established, it is a simple matter to remove concentrate and middling through suitable openings located near the inner radius of the spiral.
>
> "For particles of lower density, which sometimes are not entirely lifted into the main stream at the inner radius of the spiral,

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*Probably meant to be "normal".

wash water is added to the inner edge of the stream. This wash water tends to wash off lighter material on the surface of the heavier and return it to the concentration zone".

A test was made with the Humphreys spiral by the Humphreys Investment Co. on a sample of minus 1/8-inch bituminous coal from the Crowsnest Pass District. A yield of 78.3% of washed coal with an ash of 11.3% was obtained from a feed containing 17.4% ash. This left a refuse product containing 39.3% ash. "Theoretically" perfect cleaning on this coal as shown by a float-and-sink test on the feed would have been 87.5% yield at 11.3% ash leaving 12.5% refuse with an ash of 57.5%. The Fraser-Yancey efficiency[*] for this test was therefore $\frac{78.3}{87.5} \times 100 =$ 89.5%. These results indicate that there was considerable loss of Clean coal. However, because of its simplicity and low cost this process may find application as a preliminary cleaner. For example, if a 11.3% ash product is acceptable, the fine coal could first be cleaned in a Humphreys spiral and the refuse might then be treated in a flotation cell.

The spiral process has the advantages of low cost. The cost of cleaning (31) in the United States is estimated at 7.5 cents per ton of minus 4-mesh feed. The installation cost in the United States is estimated at $1000 per ton per hour. These costs would probably be considerably higher in Canada.

Froth-Flotation

Coal finer than 65 mesh cannot be cleaned satisfactorily by normal gravity concentration methods. This is primarily because the fine particles do not follow the same laws of settling as do the coarser

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[*] See p. 51 for explanation of Fraser-Yancey Efficiency.

sizes. At present the only method which is acceptable for cleaning this size range is froth flotation. According to Needham (34) the froth flotation process is usually acceptable for cleaning the whole size range of minus 14-mesh coal, although the cleaning is poorer for the minus 100-mesh size than it is for the 14- to 100-mesh range. Many froth flotation installations have been made in Europe, where it is essential to recover as much of the combustible material as possible. As far as can be determined, no froth flotation installations have as yet been made in this country.

Two installations of small commercial kerosine flotation plants, treating 12 and 22 tons per hour respectively, have been made in Alabama.(39) The kerosine flotation process is similar to the conventional froth flotation process, except that the flotation reagent is kerosine, rather than the coal-tar derivatives which are often used. Operating costs for the 22 ton per hour plant were estimated at 14 cents per ton of feed, while operating costs for the 12 ton per hour plant were 24 cents per ton of feed. These costs are perhaps misleading in that they do not include depreciation or labor costs. They are based upon a price of 10 cents per gallon for kerosine as compared with a cost of approximately 25 cents per gallon in Alberta. The cost of buildings to house the plant would in all probability be much higher in Alberta than they are in Alabama where severe winter weather conditions are not a problem. Taking all these factors into account it is probable that the cost of cleaning fine coal by the kerosine flotation process would be at least double that quoted by Schiffman(39) for the 12 ton per hour plant. The cost of drying the wet product, would, of course, be additional.

A typical size analysis of a mine-run coal from a Crowsnest Pass bituminous mine shows that 61.6% of the coal is minus 1/2-inch,

34.2% minus 1/4-inch, and 7.6% minus 48-mesh. At the present time flotation is probably out of the question for treating the minus 1/4-inch coal which comprises 34% of the total mine output. However, if a cheap method of cleaning the 1/4-inch to 48-mesh fraction were available, it might be profitable to clean the minus 48-mesh coal by flotation.

PNEUMATIC PROCESSES (12)

The most common types of pneumatic processes for cleaning coal in use today are the pneumatic jig or air-flow cleaner and the pneumatic table. A third type is the Brusset Vacuum-jig. Several cleaners of this type are in operation at the cleaning plants of West Canadian Collieries at Blairmore. No operating data on the vacuum-jig are available in the literature, so that no assessment of its performance can be made.

Pneumatic Tables (17)

At the present time, in Alberta, most of the minus 1/4-inch coal that is cleaned is treated on pneumatic tables. The majority of these tables are built by the American Coal Cleaning Corporation. The several models built by this company differ mainly in the shape of the table deck. The earliest model was the C J which was followed by the S J, the Y, the R and the Twin-Dex models. The V Table developed by the Birtley Company in England is similar to the American R Table.

The pneumatic table consists of a perforated riffled deck supported on toggles and reciprocated longitudinally with a jerking motion. The motion of the table moves the particles of coal and impurity longitudinally along the deck toward the refuse end of the table. A slight upward component of the deck motion, imparted by the toggles, assists the current of air rising through the perforations of the deck

in stratifying the particles. The lighter coal particles are buoyed up and flow across the riffles to discharge along the side of the deck. Their movement is aided by the slope of the deck in this direction. The heavier refuse particles caught behind the riffles are moved toward the end of the deck, where they are discharged. Middlings are discharged along the side of the table between the clean coal and refuse.

The Air Flow Cleaner or Pneumatic Jig (12)

This type consists essentially of a stationary, pervious deck, sloping several inches per foot from the feed to the discharge end, through which rises a pulsating current of air, supplied by a centrifugal fan, is caused to pulsate by the rotation of a shutter in the air duct. The coal, as it flows along the sloping deck, is stratified by the pulsating air current. The upper strata of the bed (clean coal) are discharged over an adjustable weir, while the underlying strata (refuse) are removed through a rotating valve at a lower level.

Stephens-Adamson Air-Sand Cleaner (12)

This cleaner is based on Fraser's Air-Sand process. Air is bubbled through a porous plate through a mass of dry sand 30 to 80 mesh in size. The coal floats on this aerated sand mass and the refuse sinks.

A demonstration model of this type of cleaner was loaned to the Research Council of Alberta by the Stephens-Adamson Manufacturing Company. The essential part of this cleaner was a launder-type separator through which sand flowed at a relatively rapid rate, the flow being induced by the launder being inclined at an angle of 5° to the horizontal and being given a reciprocating motion. The floor of the separator consisted of three porous, alundum plates through which air passed upward

and was released in fine bubbles uniformly over the bottom of the separator. Two vertical shale chutes were provided in the floor of the separator, one after the first porous plate and the other between the second and third plates. The sand was delivered continuously to the upper end of the separator from a storage hopper, the flow being regulated by a gate. As the sand passed through the separator it was aerated and fluidized by the air passing through the porous plates. The sand was discharged from the separator to a de-sanding screen for return to the sand hopper.

Several tests were made with this model on a high-volatile C bituminous coal from the Sterling Collieries in the Coalspur Area of Alberta. The sample used was 1/8- to 1/4-inch in size with an ash of 20.1%. The cleaning results obtained were good when compared with those given by other pneumatic devices. In one typical test the yield of washed coal was 79.5% with an ash content of 11.9% leaving 20.5% refuse with an ash content of 55.4%. The Fraser Yancey efficiency was 94% while the probable error* was 0.155. Conditions for this test were quite favorable since the feed was perfectly dry and the size ratio was two to one or less. Another factor which affected the performance was the rate of feed. It was found that the cleaning was most efficient when only a single layer of coal was allowed to flow down the primary cleaning section.

Perhaps it should be emphasized that the results of these tests made with the demonstration model do not necessarily apply to the full-size Stephens-Adamson air cleaner.

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*See p. 63 for definition of probable error.

As far as can be determined, only one installation of this type has been made in Canada--that at the Franklin Mine of the Bras D'Or Coal Company at Bras D'Or, Nova Scotia. It is stated that this Stephens-Adamson Cleaner which has been in operation for approximately two years is treating 60 tons of 4-1/2- to 1-1/4-inch coal per hour. The raw feed coal has an ash content of 15% and a sulphur content of 5.7%. The cleaned product has an ash content of 9.2% and a sulphur content of 4.3% whilst the average amount of refuse is 8.5%.

III THEORY

SETTLING VELOCITY (9)

The settling velocity of a particle under free settling conditions may be determined from a force-balance on the particle. The forces acting on the particle in absolute units are:

(1) the gravitational force downward = mg

(2) the buoyant force of the liquid upward = wg

(3) the resisting force = F'_R

where m = mass of particle

w = mass of fluid displaced by particle

g = acceleration due to gravity.

Then the resultant force tending to move the particle downward is

$$F' = mg - wg - F'_R \qquad (1)$$

since $F' = ma = m\frac{dv}{dt}$

$$m\frac{dv}{dt} = mg - wg - F'_R \qquad (2)$$

For laminar flow Stokes (41) showed that the force resisting the motion of a spherical particle is

$$F'_R = 3\pi D\mu v. \qquad (3)$$

where D = diameter of spherical particle

μ = viscosity of fluid

v = velocity of particle relative to the fluid.

Substituting this value for F'_R for a spherical particle in Eqn. (2).

$$\frac{\pi D^3}{6}\rho_s \frac{dv}{dt} = \frac{\pi D^3}{6} g. (\rho_s - \rho) - 3\pi D \mu v \qquad (4)$$

where ρ_s = density of particle

ρ = density of liquid

Dividing both sides by $\frac{\pi D^3}{6}\rho_s$

$$\frac{dv}{dt} = g\frac{(\rho_s - \rho)}{\rho_s} - \frac{18\mu v}{D^2 \rho_s} \qquad (5)$$

At the maximum or terminal velocity $\frac{dv}{dt}$ = o.

$$g\frac{(\rho_s - \rho)}{\rho_s} = \frac{18\mu v_m}{D^2\rho_s} \qquad (6)$$

$$v_m = g\frac{D^2(\rho_s - \rho)}{18\mu} \qquad (7)$$

This is the form in which Stokes law is usually given and is applicable to a non-porous, incompressible, spherical, solid particle in an incompressible fluid in laminar flow.

Newton (35) developed an expression for the resisting force F'_R as follows:

$$F'_R = f' A \frac{\rho v^2}{2} \qquad (8)$$

where A = representative area of the particle

f' = friction factor

For a sphere, the representative area A may be the projected area $\frac{\pi D^2}{4}$ and for this special case

$$F'_R = f_D \frac{\pi D^2 \rho v^2}{8} \qquad (9)$$

where f_D = friction factor for this specific case.

Substituting this value for F'_R in equation 2 for a spherical particle.

$$\frac{\pi D^3 \rho_s}{6} \frac{dv}{dt} = \frac{\pi D^3 g}{6} (\rho_s - \rho) - f_D \frac{\pi D^2 \rho v^2}{8} \qquad (10)$$

Dividing by $\frac{\pi D^3}{6} \rho_s$

$$\frac{dv}{dt} = g \frac{(\rho_s - \rho)}{\rho_s} - \frac{3}{4} f_D \frac{\rho}{\rho_s} \frac{v^2}{D} \qquad (11)$$

At max. or terminal velocity v_m, $\frac{dv}{dt} = 0$

$$g \frac{(\rho_s - \rho)}{\rho_s} = \frac{3}{4} f_D \frac{\rho}{\rho_s} \frac{v_m^2}{D} \qquad (12)$$

$$v_m = \sqrt{\frac{4}{3} \frac{g D}{f_D} \frac{(\rho_s - \rho)}{\rho}} \qquad (13)$$

Equation 13 is frequently called Newton's Law, expressing the terminal velocity for falling spheres in terms of a variable friction factor f_D. This equation may be used for laminar or turbulent flow providing that the correct value of f_D is employed. Solving equation 13 for f_D

$$f_D = \frac{4}{3} \frac{g D}{v_m^2} \frac{(\rho_s - \rho)}{\rho} \qquad (14)$$

If the value for vm for laminar flow of equation 7 is substituted for vm in equation 14.

$$f_D = \frac{4}{3} \frac{g D}{v_m} \frac{(\rho_s - \rho)}{\rho} \frac{18 \mu}{gD (\rho_s - \rho)} \qquad (15)$$

$$f_D = \frac{24\mu}{D\,v_m\rho} \tag{16}$$

$$f_D = \frac{24}{Re.} \text{ since } \frac{Dv\rho}{\mu} = Re. \tag{17}$$

Under laminar flow conditions, equation 17 may be used directly to find the friction factor f_D or equation 17 may be expressed in logarithmic form:

$$\log f_D = \log 24 - \log Re.$$

Thus, when "f_D" is plotted as a function of "Re" on a log-log scale, the resulting curve is a straight line with a slope of minus one for "Re" up to approximately three. (Fig. 1)*. In the turbulent flow region ("Re" greater than 300 or 400), the value for "f_D" becomes nearly constant, independent of "Re" until a "Re" of about 200,000 is reached when the friction factor decreases sharply. The reason for this sharp decrease is that an eddy is formed immediately behind the particle; the particle and eddy travel together, thus forming a streamlined body.

The transition from laminar to turbulent flow is rather indefinite, as indicated in Fig. 1, i.e., there is no sharp break from the straight sloping line representing laminar flow to the horizontal line delineating turbulent flow where "f_D" is practically constant.

THE EFFECT OF PARTICLE SHAPE (3)

The equations in the foregoing subsection have been developed for the terminal velocity "vm" of spherical particles. This is a special case since in nature most particles have irregular shapes. The shape of a particle may be defined in terms of the sphericity ψ,

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*Figs. 1 and 2 reprinted from Unit Operations by Brown, C.G., et. al.

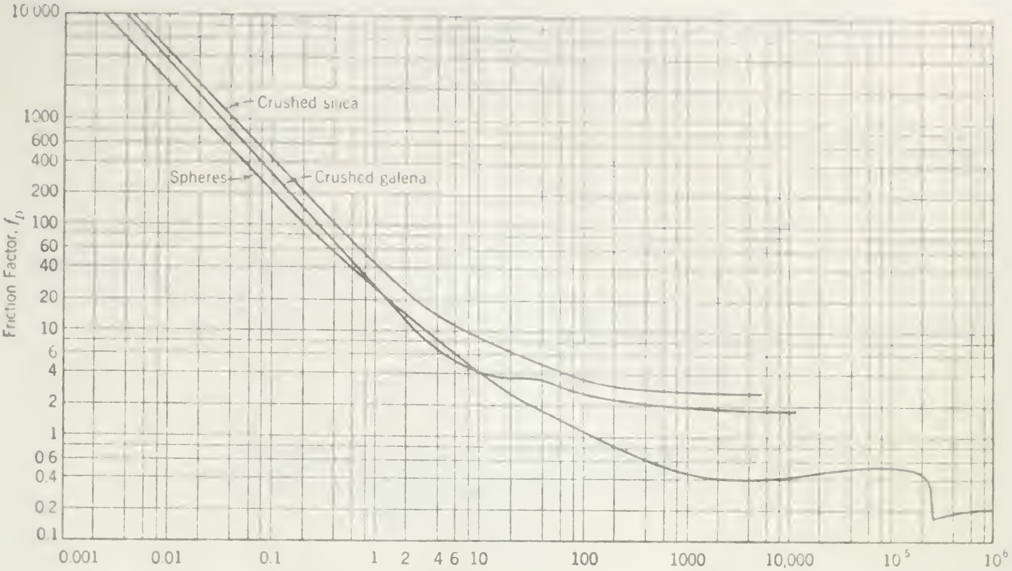

Fig.1 Friction factor, or drag coefficient, versus Reynolds number for crushed solids and spheres flowing through fluids

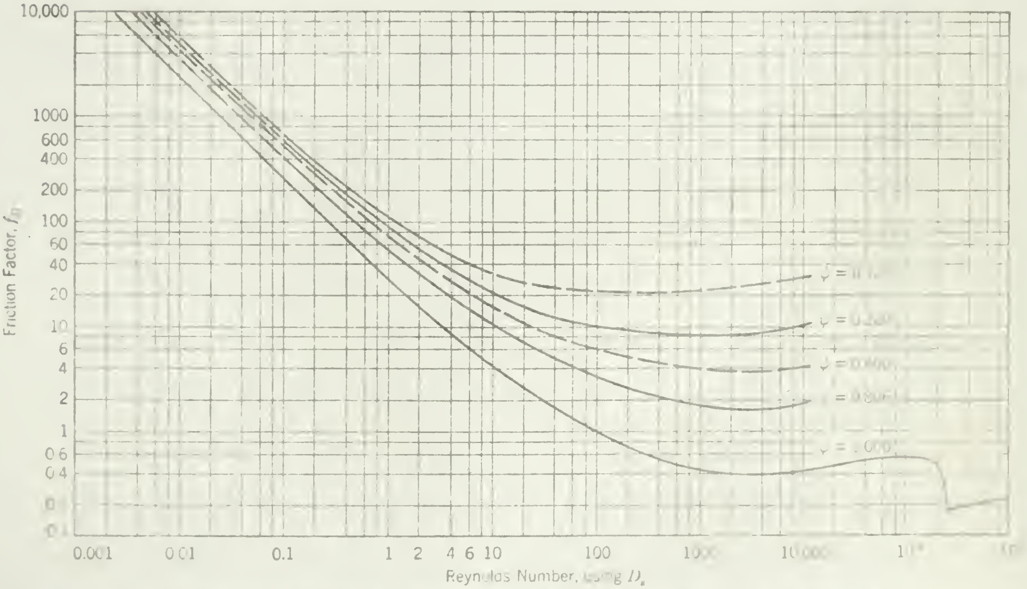

Fig.2 Friction factor, or drag coefficient, versus Reynolds number for particles of different sphericities

(These diagrams reprinted from Unit Operations by Brown G.G. et al.)

$$\text{where } \psi = \frac{\text{surface area of a sphere having the same volume as the particle.}}{\text{surface area of the particle}}$$

$$= \frac{D_{avg}}{D_s} \; \frac{1}{n} \qquad (16)$$

where D_{avg} = average screen size

D_s = diameter of sphere having same volume as the particle ($D_s = D_{avg}$ for a spherical particle)

$$n = \frac{\text{specific surface}^{*}\text{ of the particle}}{\text{specific surface of a sphere with diameter } D_{avg}}$$

Fig. 2 shows the family of curves resulting when "f_D" is plotted against "Re" using the sphericity, ψ, as a parameter. These curves are based on a "diameter", D_s, which is not the same dimension as the size of a particle determined from a screen analysis. The screen size approximates the second largest dimension of the particle. For example, a prism a by $2a$ by $3a$ has the effective dimension $2a$ as its "size" in screen analysis, but the diameter of a sphere having the same volume is 2.25 a. Brown (9) presents a table of factors of $\frac{D_s}{D_{avg}}$ for various shaped particles. Thus, in order to use the curves in Fig. 8, an estimation of the particle shape would have to be made by microscopic examination. The screen size, D_{avg}, would then have to be multiplied by the factor $\frac{D_s}{D_{avg}}$ to get the value of D_s to be used in the settling equations or the friction factor plot in Fig. 2. The curves labelled "crushed silica" and "crushed galena" in Fig. 1 were determined experimentally

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[*] The specific surface is defined as the surface area per unit of mass.

and may be used directly without computing the sphericity. The displacement of these two curves is due to the use of the screen size, D_{avg}, rather than D_s for the particle dimension.

Values of the sphericity, ψ, for coal have been determined experimentally by several workers. Gaudin (24) cites values of 0.5 to 0.7 for coal and minerals whereas Skinner et.al. (40) quote a value of 0.4 for coal. Oberholtzer (36) obtained values of 0.36 to 0.49 for 150- to 200-mesh Alberta coals; the lower value was for a sub-bituminous and the higher value for a bituminous coal. However, Oberholtzer thought that these values were low because of screening errors and believed that a value of 0.6 was more nearly correct.

SEPARATION DUE TO DIFFERENCE IN DENSITY (9)

The separation of solid particles on the basis of differences in their densities is known as sorting. When materials of the same density are separated on the basis of their size, the operation is known as sizing. Since feeds of absolutely uniform size are never obtained in actual operation, sizing is always involved to a certain extent in every sorting operation. Sorting depends upon the principle that the upward or downward direction of the flow of solid particles through a fluid depends upon the density of the solid relative to that of the fluid. The solid particles may be sorted by introducing them into a body of a fluid having a density intermediate to the densities of the solids. The particles with a density less than that of the fluid will float, and the particles with a density greater than that of the fluid will sink. A suspension of very fine solid particles in a fluid will have a similar effect as the simple fluid providing that the proper

amount of fine particles is added to give the required effective specific gravity. Suspensions of this sort are used to provide the separating baths employed in the heavy-media processes of coal-cleaning.

The effects of both size and density of particles can be considered in combination to calculate the range of sizes of a feed that can be separated according to density. This is done by employing the concept of "equal falling" particles (10), which are the sizes of particles of two different materials to be sorted having equal settling velocities. Under laminar flow conditions

$$v_m = \frac{g\, D_A^2\, (\rho_A - \rho)}{18\, \mu} = \frac{g\, D_B^2\, (\rho_B - \rho)}{18\, \mu} \tag{19}$$

$$\frac{D_A}{D_B} = \sqrt{\frac{(\rho_B - \rho)}{\rho_A - \rho}} \tag{20}$$

where D_A/D_B is the ratio of the diameter of spherical particles of two different materials A and B having the same terminal settling velocity v_m, and is called the "spherical settling ratio".

Under turbulent conditions

$$v_m = \sqrt{\frac{4\, g\, D_A\, (\rho_A - \rho)}{3\, (f_D)_A\, \rho}} = \sqrt{\frac{4\, g\, D_B\, (\rho_B - \rho)}{3\, (f_D)_B\, \rho}} \tag{21}$$

$$\frac{D_A}{D_B} = \frac{(\rho_B - \rho)}{(\rho_A - \rho)} \cdot \frac{f_{D_A}}{f_{D_B}} \tag{22}$$

where D_A/D_B is again the spherical settling ratio. In many cases, as with particles of the same sphericity, the values for f_D are the same for each material and $(f_D)_A / (f_D)_B = 1$. In most cases for fine coal it can be assumed that the sphericities of the clean coal and shaly

material are approximately equal so that the above equation reduces to

$$\frac{D_A}{D_B} = \frac{\rho_B - \rho}{\rho_A - \rho} \qquad (23)$$

The "settling ratio" $(D_{avg})_A / (D_{avg})_B$ represents the ratio between the maximum and minimum "screen diameters" of particles that may exist in a sized mixture of the materials A and B, if a clean separation between these two materials is to be made by classification, using the fluid in question. The ratio $\frac{D_s}{D_{avg}}$ may be found from tables and used to find the settling ratio $(D_{avg})_A / (D_{avg})_B$. If the ratio $\frac{D_s}{D_{avg}}$ is the same for both materials the "settling ratio" is the same as the "spherical settling ratio".

HINDERED SETTLING (9)

The equations which have been derived in the previous sub-sections apply to free settling. Such conditions are not usually encountered in practice where "hindered settling" occurs. Under hindered settling conditions the particles interfere with one another and the equations for settling velocity (equations 7 and 13) do not apply. If, however, the apparent density of the solid-liquid mixture is substituted for the density of the separating fluid, an approximate value of the settling ratios may be found. It will be seen from equations 20 and 23 that if ρ is increased and ρ_A is smaller than ρ_B, the ratio of the diameter of equal settling particles D_A/D_B becomes larger. This effect is produced by hindered settling, in which the particles, interfering with one another as they settle, act as a sorting bed of higher density than the fluid itself. The separation is thus improved under hindered settling conditions. The capacity of the equipment is

greatly increased if hindered settling rather than free settling conditions exist, since a larger amount of material can be passed through a given cross-sectional area.

SEPARATION USING CENTRIFUGAL FORCE

The force acting on a particle can be greatly increased by subjecting it to centrifugal force. The centrifugal force (21) may be expressed as

$$Fc = \frac{mu^2}{r} \tag{24}$$

where F_c = centrifugal force

m = mass of the particle

u = peripheral velocity

r = radius of curvature or path

using the same absolute units as in the force-balance of equation 1. If this force F_c is now included in the force balance of equation 1, the resultant force tending to move the particle is now

$$F' = \frac{m\,u^2}{r} \text{ (in a horizontal direction toward the wall)} + mg - wg - F_R \tag{25}$$

The centrifugal component $\frac{m\,u^2}{r}$ acts in a direction normal to the gravitational and buoyant force components, mg and wg. The force acting on the particle is now a resultant of the vertical and horizontal forces (mg- wg) and $\frac{m\,u^2}{r}$ as shown in Fig. 3.

When $\frac{u^2}{r}$ is large compared with g, as is usually the case in centrifugal separation, the particle tends to move in a horizontal direction towards the wall as shown in Fig. 3. For the cyclone separations performed in the present investigation the inlet velocity was

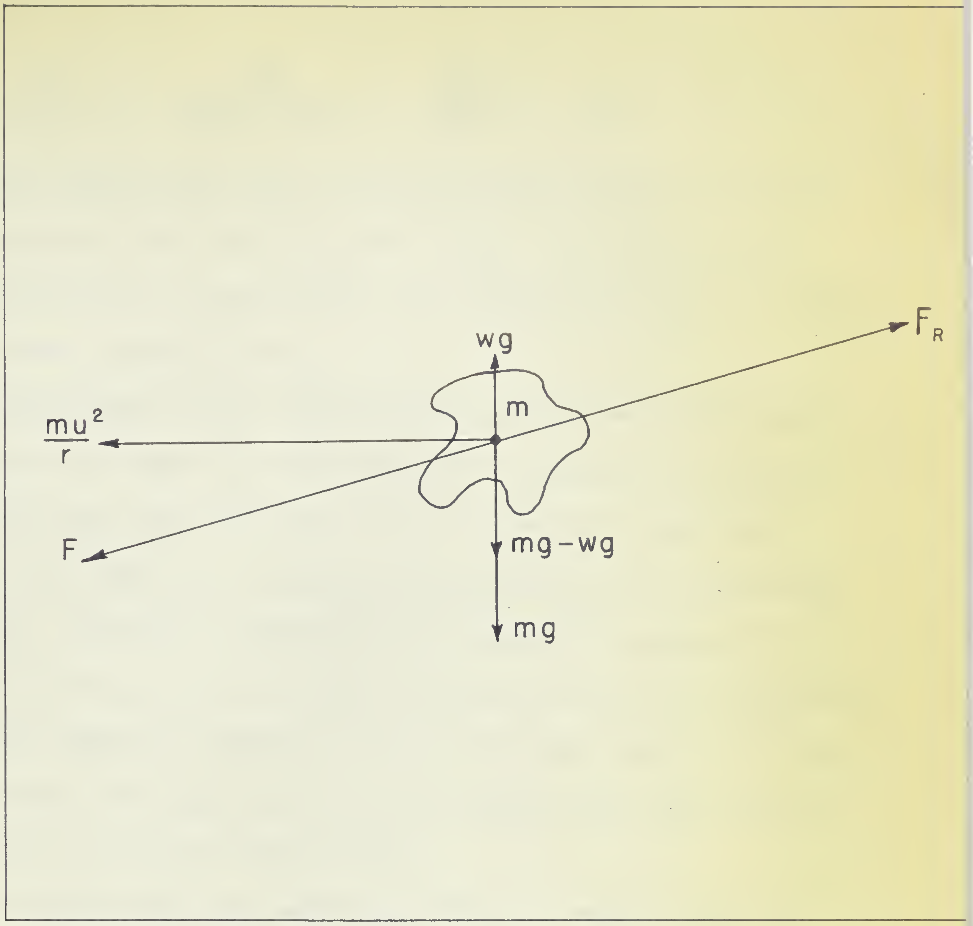
wg
m
$\frac{mu^2}{r}$
F_R
F
mg-wg
mg

Fig. 3 Diagram illustrating the forces acting on a particle of mass "m" which has been subjected to centrifugal force.

approximately 12 f.p.s. and for the three-inch cyclone at the inlet $r = 0.125$ ft.

$$\frac{u^2}{r\ g} = \frac{12^2}{0.125 \times 32.2} = \frac{1152}{32.2} = 35.8$$

Therefore the centrifugal force was approximately 36 times as great as the gravitational force near the cyclone inlet. It is thus evident that the introduction of centrifugal action greatly increases the forces tending to make particles settle.

Centrifuges are not used for coal cleaning because the separating liquid must either be a true liquid or a suspension of particles so small that they would not settle out if subjected to centrifugal force. A true liquid such as carbon tetrachloride has the disadvantage of high cost. According to Driessen (21), the use of a suspension in a centrifuge is not practical, because the particle size in the suspensions normally used (barytes, magnetite, etc.) is too great and the particles tend to separate out along with the shale, leaving clear water instead of a suspension as the separating medium.

A device which uses centrifugal force to separate coal and shale but which overcomes the difficulties encountered with the centrifuge is the D.S.M. cyclone. The cyclone can be used as a thickener, in which case the working principles are much the same as in the well-known air cyclone. The cyclone can also be used to separate materials of different density if the separating liquid has a density intermediate between that of the materials being separated, a suspension of very fine (minus 325 mesh) particles of some material such as magnetite or barytes may be used

as the separating liquid. Driessen (21) states that the suspension particles do not settle out in the cyclone as they do in the centrifuge because "the suspension in the cyclone is not relatively stationary but in constant motion so that the small suspension particles are prevented from settling against the inner wall of the cone".

IV REVIEW OF LITERATURE AND THEORY OF CYCLONE WASHER

Originally, the cyclone washer was developed by workers at the Dutch State Mines as a thickener in connection with the Loess Heavy-Media Coal Cleaning process. The use of the cyclone as a thickener was first reported by Driessen (17) immediately before the war in 1939. Several reports (13, 14, 15, 16, 19) have been published since that time on the theory and use of the cyclone thickener. The Dutch discovered, accidentally, that the cyclone could be used as a coal cleaner as well as a thickener. In 1945, soon after the war ended, Driessen presented a paper describing the use of the cyclone as a coal washer (18). This paper and another by the same author (19) showed that the cyclone performed very sharp separations on fine coal. These reports did not give any details as to the effect of the various operating variables of the cyclone on its performance.

In 1947, Geer and Yancey (25) of the United States Bureau of Mines investigated the influence of different operating variables on the performance of a cyclone used to clean Pennsylvania and Washington bituminous coals. The variables investigated were underflow and overflow-opening diameters, feed-tube opening diameter, feed-inlet pressure and variations in the amount of impurity in the feed. The results of this investigation showed that when the overflow opening was made larger or conversely, the underflow opening for the refuse was made smaller, the cyclone made separations at higher specific gravities. It was found also, that the size of the inlet feed opening had little effect on cyclone performance. When the feed pressure was varied, the efficiency of the separation dropped off as the pressure was decreased from 20 to 10 p.s.i.g. Sand was mixed in with the raw

feed coal to determine the effect of varying the amount of impurity in the feed. These tests showed that the amount of refuse removed varied directly with the amount of impurity present.

The results of work done by Van der Walt on the cyclone washer at the Fuel Research Institute of South Africa were published in 1949 in two papers (44, 45). This work investigated the influence of the apex angle of the cyclone, design of the overflow opening, various combinations of overflow and underflow openings, feed pressure, size analysis of the feed, specific gravity of heavy medium slurry, and pulp ratio of the slurry. The object was to obtain a low-ash coking coal, and to that end the separations were performed at comparatively low specific gravities in the region of 1.35. As a result, the yields of washed coal were also low, ranging from 25 to 40%. Generally, for ordinary coal-washing, the yields of washed coal vary from 65-95%. Van der Walt found that a 25° cyclone apex angle gave better separations than a 38° apex angle, and that the specific gravity of separation was less with the 25° cyclone than that obtained with the 38° cyclone. Van der Walt's experiments also demonstrated that the addition of a vortex finder tube for the overflow exit from the conical section of the cyclone improved the performance. The length of this tube was not critical provided that it was not abnormally long and not less than 1-1/4-inches in length for a 9-1/2-inch diameter cyclone. The conclusions reached by Van der Walt as to the diameter of the overflow and underflow openings, were that the largest possible overflow should be used together with the underflow opening necessary to give the required specific gravity of separation. The effect on cyclone performance of varying the inlet feed-pressure seemed to be small, as long as the pressure was kept above a critical

value of 7.5 p.s.i.g. To determine the effect of particle size, a test was carried out with 1/4-inch to 100-mesh coal. The cleaning was found to decrease appreciably for coal smaller than 48 mesh.

Several papers on the cyclone washer were presented at the First International Conference on Coal Preparation at Paris 1950. The Centre d'Etudes et Recherches des Charbonnages de France or Cerchar as it is more commonly known, have made numerous tests on the cyclone washer (4). It was shown that the best results were obtained when the inlet and outlet exit diameters of the cyclone were approximately equal and when the specific gravity of separation approached the value of the specific gravity of the medium. With a suspension specific gravity of 1.45, sharp separations (probable error 0.035) were obtained on coal down to 30 mesh in size. With a medium of 1.26 specific gravity, the probable error was low (0.046) for particles as small as 150 mesh. However, this separation was performed at a relatively low specific gravity of separation so that losses of clean coal were probably quite high.

In Belgium, Burton (11) conducted investigations with an 80-mm. (approximately 3-inch) diameter cyclone using magnetite and water as the heavy medium. These tests were made on minus one m.m. (approximately 16 mesh) coal. He observed that the Probable Error increased with specific gravity of separation and attributed this to the increase of "viscosity" in the separating zone. Burton also found that cleaning with a probable error of 0.084 was performed on coal as fine as 200-mesh.

Driessen who made a study of the theory of flow in the cyclone (20) assumed that the flow could be compared with a two-

dimensional vortex flow, and applied the Navier-Stokes equations* to obtain a solution for the tangential velocity as a function of the radial distance from the center of the cyclone. In order to solve the Navier-Stokes equations the following assumptions were made: (1) an incompressible fluid, (2) steady flow, (3) two-dimensional flow, (i.e. no flow in an axial direction), (4) the radial velocity negligible as compared with the tangential velocity (5) the maximum tangential velocity to occur at the outlet radius.

The general solution obtained for the tangential velocity was

$$v = \frac{c}{n+1} r^n + \frac{c_1}{r}$$

where v = tangential velocity

c = resultant velocity

r = radial distance from center

c = constant of integration

$$n = -\frac{E}{2\pi\nu'} + 1$$

where $E = -2\pi ur$

ν' = "turbulent viscosity coefficient"

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* The Navier-Stokes Equations as given by Driessen are:

$$\frac{\partial u}{\partial t} + \frac{\partial u}{\partial r} + \frac{v}{r}\frac{\partial u}{\partial r} + w\frac{\partial u}{\partial z} - \frac{v^2}{r} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + V_1$$

$$\frac{\partial v}{\partial t} + \frac{\partial v}{\partial r} + \frac{v}{r}\frac{\partial v}{\partial \phi} + w\frac{\partial v}{\partial z} + \frac{uv}{r} = -\frac{1}{\rho r}\frac{\partial p}{\partial \phi} + V_2$$

$$\frac{\partial w}{\partial t} + \frac{\partial w}{\partial r} + \frac{v}{r}\frac{\partial w}{\partial z} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + V_3$$

where u = radial velocity component
v = tangential velocity component
w = axial velocity component
r and ϕ = polar co-ordinates
z = axial co-ordinate

ρ = density
t = time
p = pressure
V_1, V_2, V_3 = viscosity terms

Driessen conducted experiments with a flat cyclinder which represented an approximation of a this section of a cyclone. Air was blown through the cylinder and pressure distribution measurements were made at various radial distances from the center of the cylinder. From these experimental data the tangential velocities were computed. These computed tangential velocities were plotted against the radial distances from the center of the cylinder on a log-log scale. The tangential velocities given by the solution of the Navier-Stokes equations were also plotted versus the radial distances on a log-log scale. Various values of the term "n" were assumed in order to calculate these latter tangential velocities. It was found that a value of $n = -1$ gave a curve which agreed very closely with the curve obtained from the experimental data. From this value of $n = -1$, the value of the "turbulent viscosity coefficient", ν', was determined. Driessen states that "due to the turbulence caused by the walls and by the high relative velocities between adjacent layers a force will be created which can mathematically be interpreted as an increased kinematic viscosity. This "increased kinematic viscosity" is the "turbulent viscosity coefficient", ν'. These experiments were conducted with air as the fluid medium. More work remains to be done before the validity of Driessen's work can be assessed. One assumption that may be questionable is that of two-dimensional flow, i.e. no flow in an axial direction. Although this assumption was probably quite reasonable for Driessen's experiments with a flat cyclinder, it may be doubtful whether there is any justification for assuming such a condition to exist in a conical cyclone.

V METHODS USED FOR EVALUATING COAL-WASHING PERFORMANCE

In this investigation it was decided to determine the relative importance of the operating variables by conducting a series of tests in each of which there was, as far as could be determined, only one variable. The relative importance of any variable could then be appraised by the use of some reliable basis of comparison. Of the many methods which have been proposed for evaluating the performance of coal-washing equipment, the Fraser-Yancey Efficiency (22), the Anderson Efficiency (1), the Probable Error developed by the French (3, 42) and Driessen's Error Area (18) are those most used in Europe and America.

FLOAT-SINK ANALYSIS

All of the above methods are based upon float-sink analyses of either the raw feed coal or the products. For a float-sink analysis a sample of the coal is placed in an organic liquid of 1.30 specific gravity. The float coal is skimmed off, dried and weighed. The material that sinks is drained and placed in a liquid with a specific gravity of 1.40; the float coal is again dried and weighed. This procedure is repeated with heavier liquids to give data such as that shown in the first two columns of Table I. The third column, cumulative weight per cent, is computed from the preceding columns and gives the weight per cent floating at a definite specific gravity, e.g., 78.9% of the total feed floated at 1.60 specific gravity. An ash analysis of each specific gravity fraction is made and these data are given in the fourth column. The cumulative ash content per cent shown in the last column is calculated from the preceding columns and gives the ash content of the coal floating at various specific gravities, e.g., the cumulative ash content

of the 78.9% of coal floating at 1.60 is 9.2%. The cumulative weight per cent of float is plotted against the cumulative ash content to give the curve shown in Fig. 4. The so-called "theoretical yield" at a certain ash content can be obtained from this curve e.g., for a washed-coal product containing 12% ash, the curve indicates that with perfect recovery the yield should be 87%; this value is the "theoretical yield". The dashed portion of the curve extrapolated to zero per cent cumulative weight of float demonstrates the "inherent ash" content of the coal (2.5% in this case).

TABLE I

Example of Float - Sink Data for Raw Feed Coal

(Cadomin 10- to 100-mesh)

Specific Gravity Fraction	Weight of Fraction (Float) %	Cumulative* Weight (Float) %	Ash Content of Fraction** %	Cumulative Ash Content (of Float) %
Float 1.30	24.4	24.4	3.26	3.3
1.30 - 1.40	33.5	57.9	8.05	6.0
1.40 - 1.60	21.0	78.9	17.92	9.2
1.60 - 1.80	7.5	86.4	38.10	11.7
1.80 - 2.00	4.6	91.0	53.05	13.8
Sinks 2.00	9.0	100.0	75.01	19.3
	100.0			

* ** All weight percentages and ash contents, given in this thesis, are on a dry basis.

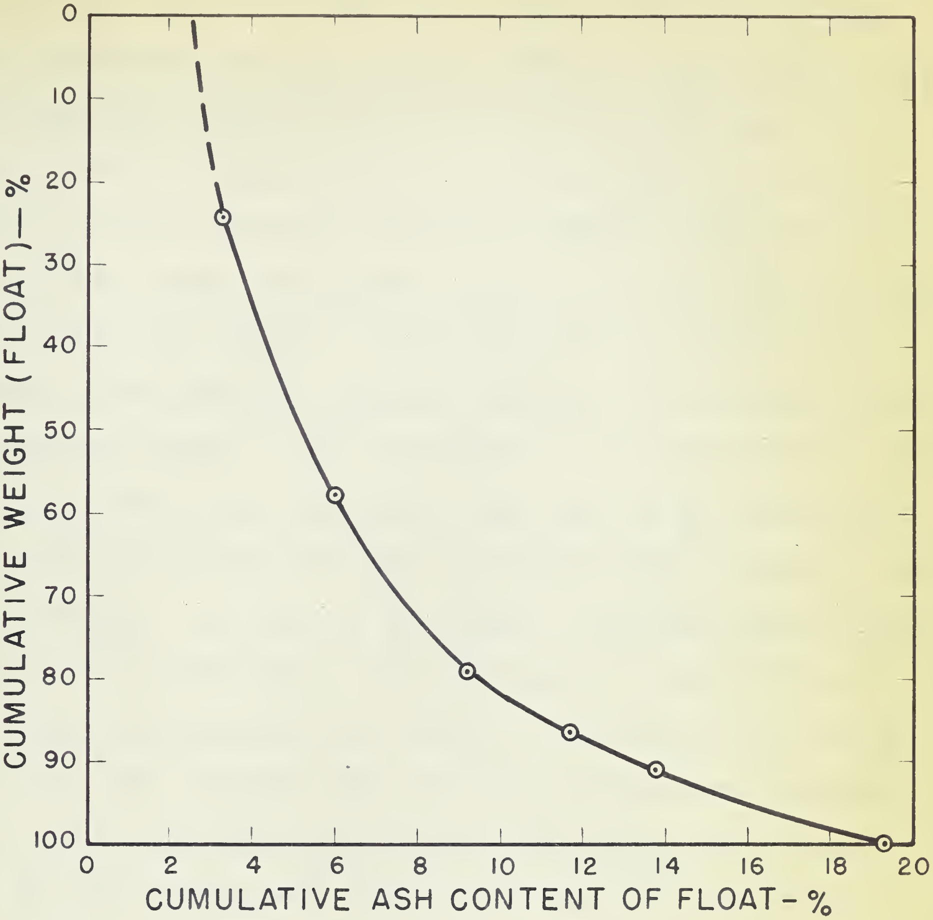

FIG. 4 CUMULATIVE FLOAT VS. CUMULATIVE ASH CURVE

A weakness in the use of float-sink analyses for appraising the cleaning performed by a coal washer is the effect of particle size of the coal. It is conceivable that a piece of material containing bands of both coal and shale may have a different specific gravity than the same material broken up into several smaller pieces e.g., the specific gravity of a lump of coal may be 1.40, but when it is broken in two, the specific gravity of one portion containing mostly clean coal may be 1.30, whereas, the specific gravity of the other containing more shale may be 1.50. Thus, the size of the coal has an effect on the results of the float-sink analysis. Similarly, the float-sink analysis depends upon whether or not size reduction of the feed coal takes place. Size degradation of the feed usually does occur in the wet-washing of coal; this is especially true when the friable Alberta bituminous coals are wet-washed. An example of the effect of immersing Cadomin bituminous coal (10- to 100-mesh) in water and mixing is shown in Table II. The weight percentages and ash contents of the various size fractions of the new coal are shown under the heading "Before water immersion". The other heading "After water immersion and drying" gives the data for the size fractions after the coal was mixed with water for one hour and allowed to stand in water for three hours, then drained on a 100-mesh screen and dried. The particles smaller than 100-mesh were therefore lost. These data illustrate that the amount of each size fraction (with the exception of the 80- to 100-mesh fraction) was less after the water immersion, showing that size degradation of each fraction did occur. The data also demonstrate that the ash content of each size fraction was less after water immersion, thus giving evidence that the shale breaks down to a greater extent than the coal. This is further

TABLE II

Data Illustrating Effect of Size Degradation on Ash Contents and Weight Percentages of Various Size Fractions of Cadomin 10- to 100-mesh Coal.

	Before water immersion		After water immersion and drying	
Size Fraction (Tyler mesh)	Weight %	Ash Content %	Weight %[*]	Ash Content %
10 - 14	19.5	23.3	14.3	19.0
14- 28	36.9	19.3	32.8	16.7
28 - 48	28.5	16.9	25.9	15.7
48 - 65	10.3	16.8	9.3	15.7
65 - 80	3.6	18.4	3.1	15.7
80 - 100	1.2	19.6	2.4	15.1
	100.0		87.8	
Ash Content of Total Sample		19.1%		16.6%

[*] Weight percentages given in terms of original weight of sample.

proven by a material balance on ash of the total sample, which shows that the ash content of the 12.2% of material finer than 100-mesh was 37%.

FRASER-YANCEY EFFICIENCY

The most widely used method for evaluating clean coal performance is probably the Fraser-Yancey Efficiency; it is the ratio, expressed in per cent, of the actual yield of washed coal over the "theoretical yield" of float coal. The "theoretical" yield is found from the cumulative weight of float versus cumulative ash curve (Fig. 4) at the same ash content as that of the washed coal e.g. if the actual yield of washed coal were 80% and the ash content of this washed coal were 12%, the Fraser-Yancey Efficiency would be calculated as follows: the yield of float coal at this ash content of 12% found from the cumulative float versus cumulative ash curve in Fig. 4 is 87%.

The Fraser Yancey Efficiency

$$= \frac{\text{Actual Yield of Washed Coal.}}{\text{"Theoretical" Yield at same Ash Content as Washed Coal.}} \times 100 \quad \%$$

$$= \frac{80}{87} \times 100 \quad \% \quad = \quad 92\%$$

In washery operation, where the quality of washed coal and the yield are of prime interest to the operator, the Fraser-Yancey Efficiency is useful since it gives a measure of the loss of salable coal. It is in fact, a material balance on coal with a certain ash-content; for the above example it is a material balance on coal with a 12% ash content. It is assumed that no size degradation occurs.

Although the Fraser-Yancey Efficiency is useful in determining the loss of clean coal, there are several factors which limit its usefulness for assessing the results of the cyclone washing tests in the present investigation. First, the Fraser-Yancey Efficiency is a function, not only of the performance of the washer, but also of the character of the coal being treated, the specific gravity at which the separation between coal and impurity is made, and the specific gravity of the feed coal. Second, size degradation of the feed greatly affected the use of this efficiency in evaluating the results of the present investigation. The ash content of the feed as calculated from the products for most of the washing experiments was approximately 17% as compared with approximately 19% for the raw feed coal, and meaningless values of the order of 103% were given when the Fraser-Yancey efficiencies were computed from the raw feed curve. A serious shortcoming of the Fraser-Yancey Efficiency is the fact that as the yield approaches 100%, the efficiency value also approaches 100%, with the anomalous result that if no refuse is removed, the efficiency for the separation is 100%. A minor objection is that there does not seem to be a large enough variation between the Fraser-Yancey Efficiency values representing good cleaning and those indicating poor cleaning. Fraser and Yancey have stated that the cleaning performance of a washer is satisfactory if the Fraser-Yancey Efficiency is 95% or greater. Using this standard, a value of 96% represents acceptable cleaning, whereas a value of 94% represents cleaning that is not acceptable.

An attempt was made in this investigation to use a uniform feed, although the separations were performed at various specific gravities. Size degradation of the feed occurred but since the ash

content as calculated from the products only varied from 17.0 to 18.0% it was believed that the amount of degradation was practically uniform for all of the washing tests. The "theoretical yield" used for computing the Fraser-Yancey efficiencies was obtained from the cumulative float versus cumulative ash curve for the feed calculated from the products of washed coal and refuse. In view of all the factors involved, it was felt that the Fraser-Yancey Efficiency was not a suitable basis for comparing the performance of the cyclone washer in these experiments, except in those instances where the ash contents of the washed-coal products were approximately equal (since the Fraser-Yancey Efficiency is actually a material balance on coal of this ash content). However, the Fraser-Yancey Efficiency was calculated for each washing test, because it gave an indication of the loss of clean coal.

TROMP DISTRIBUTION CURVE

A means for showing the sharpness of the separation effected by a coal washer, which is believed to be substantially independent of the character of the feed coal, is the distribution curve developed by Tromp (43). This curve, an example of which is shown in Fig. 5, is derived from float-sink analyses of both the washed coal and the refuse. In addition to these data the yields of the washed coal and refuse products must be known. An example of the method of obtaining the distribution curve follows: The data in Table III show the yields and specific gravity analyses for the products obtained in the cyclone separation in Experiment No. 40. The first three columns are self-explanatory. The last column shows the weight percentage of each specific gravity fraction of the feed that has gone into the washed coal. To calculate these, the various weight percentages must be

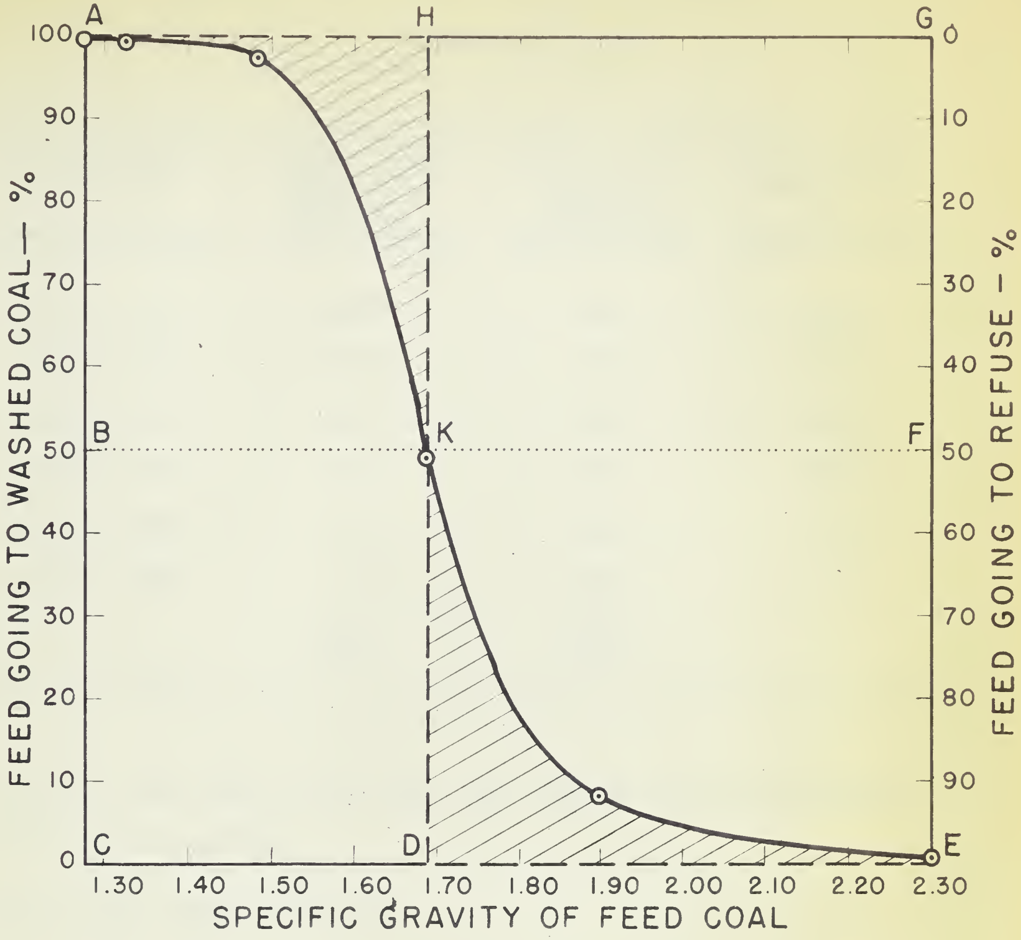

FIG.5 DISTRIBUTION CURVES
AKE - EXPERIMENT NO. 40
AHKDE - PERFECT SEPARATION
SHADED AREAS - ERROR AREA

TABLE III

Float-Sink Analyses and Yields of Products
Obtained in Experiment No. 40

Specific Gravity Fraction	Yield = 81.0% Washed Coal Weight %	Yield = 19.0% Refuse Weight %	Feed going to Washed Coal %
Float 1.30	29.0	0.5	99.6
1.30 - 1.40	46.5	1.6	99.2
1.40 - 1.60	18.6	2.3	97.2
1.60 - 1.80	5.2	23.1	48.9
1.80 - 2.00	0.6	28.5	8.3
Sinks 2.00	0.1	44.0	0.9
	100.0	100.0	

converted into terms of the feed, e.g. for the material floating at 1.30 specific gravity

Washed coal floating at 1.30

= 29.0% of 81.0% = 23.49% of the feed

Refuse floating at 1.30

= 0.5% of 19.0% = 0.10% of the feed

Total material floating at 1.30 = 23.59% of the feed

$$\text{Percentage of Float 1.30 going to Washed Coal} = \frac{23.49}{23.59} \times 100 = 99.6$$

These percentages are calculated for the remaining specific gravity fractions in a similar manner. They are then plotted against the mean specific gravity of the fraction as shown in Fig. 5. An

assumption that the lightest material in the coal has a specific gravity of 1.25 and the heaviest material a specific gravity of 2.60 is necessary in order to estimate the mean specific gravities of the fractions that float at 1.30 and sink at 2.00, which are plotted at 1.275 and 2.30 respectively. This assumption is not far wrong for most coals. For the other fractions, the mean specific gravity is taken as the specific gravity of a bath on which half of the fraction would float and half would sink. This mean value is determined from the cumulative weight of float per cent versus specific gravity curve for the feed coal. The manner in which this is accomplished is perhaps best shown by an example. The float-sink data for the calculated feed used in Experiment No. 40 is presented in Table IV.

TABLE IV

Float-Sink Data for Calculated Feed for Cyclone Separation of Experiment No. 40

Specific Gravity Fraction	Weight of Fraction (Float) %	Cumulative Weight (Float) %	Ash Content of Fraction %	Cumulative Ash Content (of Float) %
Float 1.30	23.6	23.6	3.11	3.1
1.30 - 1.40	38.0	61.6	7.46	5.8
1.40 - 1.60	15.5	77.1	17.21	8.1
1.60 - 1.80	8.6	85.7	28.98	10.2
1.80 - 2.00	5.9	91.6	45.13	12.4
Sinks 2.00	8.4	100.0	71.40	17.4

The cumulative weight per cent floating is plotted against the specific gravity; thus, 77.1% of coal floating at 1.60 is plotted at 1.60 specific gravity in Fig. 6. The weight per cent floating on a bath that would divide the 1.30 to 1.40 fraction into half float and half sink is the average of the cumulative weight per cent floating at 1.30 and 1.40 specific gravity, respectively. These values read from the cumulative weight per cent versus specific gravity curve in Fig. 6, are 23.6 and 61.6% respectively. The average of these two values is 42.6%. From the curve in Fig. 6, it is found that the specific gravity of the calculated feed corresponding to this cumulative weight per cent of 42.6 is 1.325. This is therefore, the mean specific gravity of the 1.30 - 1.40 fraction and the corresponding percentage of this fraction which has gone into the washed coal (99.2 in the last column of Table II), is plotted against this value to give a point on the distribution curve shown in Figure 5. The remaining points are found in a similar manner so that the whole curve is built up. Examination of the distribution curve AKE, in Figure 5 shows that the slope is a measure of the sharpness of separation, i.e., the steeper the slope, the sharper the separation. Theoretically perfect cleaning according to specific gravity is illustrated by the dashed curve AHKDE in Figure 5. Here the slope has become infinite, or in other words, the curve has become a vertical line at the specific gravity of separation.

The specific gravity of separation is determined from the distribution curve, and is defined as the specific gravity of material in the feed which is distributed equally between washed coal and refuse, i.e., the specific gravity at the 50% point. The specific gravity of separation has been defined by Yancey and Geer (48) in this

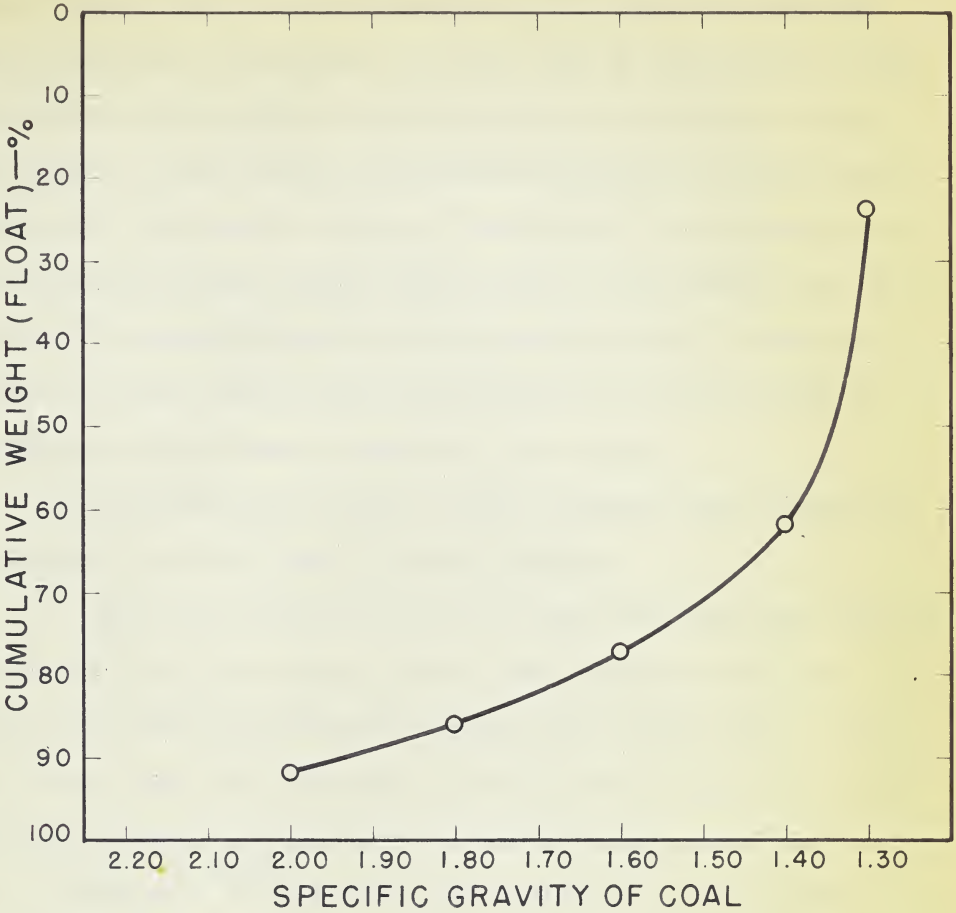

Fig. 6 Cumulative float vs. specific gravity curve for calculated feed of experiment No. 40

way, because the distribution curve in Fig. 5 shows that "a washer does not make a sharp and distinct separation, sending all material lighter than a certain specific gravity to the washed coal and all heavier material to the refuse. Instead, some of the material in each specific-gravity fraction of the feed reports to the washed coal and some reports to the refuse, the proportion reporting to either product varying with the specific gravity of the fraction. Because the separation between coal and impurity takes place in this fashion, the only logical and correct definition of the specific gravity of separation is that it is the specific gravity of material in the feed which is distributed equally between washed coal and refuse".

The shaded areas in Fig. 5 show the "Error Area" which will be discussed in detail later on in this section.

Since the distribution curve is based upon float-sink analyses of the washed coal and refuse products, the weaknesses which were pointed out under the discussion of float-sink analysis apply to the use of this curve. The influence of particle size of the coal on the float-sink analysis was assumed to be uniform since a sized feed coal (10- to 100-mesh) was used. The effect of size degradation on the results of the float-sink analyses was also assumed to be uniform for all of the experiments since the ash content of the feed as calculated from the products only varied from 17 to 18%.

THE ANDERSON EFFICIENCY (1)

This Efficiency, which is being widely used in the United States (44) is based on the concept of misplaced material developed by Yancey (48), i.e., anything in the washed coal heavier than the specific

gravity of separation is misplaced material, as is anything lighter than the specific gravity of separation in the refuse. The Tromp distribution curve is used to find the specific gravity of separation. The following is an illustration of how the Anderson Efficiency is calculated: the float-sink analyses of the washed coal and refuse products obtained in Experiment No. 35 are shown in Table V. The calculated percentage of each fraction going to the washed coal is shown in the last column. The specific gravity of separation is obtained from the distribution curve plotted from the data in the last

TABLE V

Float-Sink Data for Products of Cyclone
Separation of Experiment No. 35

Specific Gravity Fraction	Yield = 88.5% Washed Coal Weight %	Yield = 11.5% Refuse Weight %	Feed Going to Washed Coal %
Float 1.30	29.4	0.3	99.9
1.30 - 1.40	30.3	0.2	99.9
1.40 - 1.60	30.8	0.3	99.8
1.60 - 1.80	7.9	6.6	90.3
1.80 - 2.00	1.1	29.2	21.9
Sinks 2.00	0.5	63.4	4.5
	100.0	100.0	

column of Table V and is found to be 1.80*. If the coal with a specific gravity less than 1.80 is now classed as clean coal and all coal with a specific gravity greater than 1.80 is classed as refuse, the clean coal lost in the refuse is 7.4% of the total weight of refuse and the misplaced refuse in the washed coal is 1.6% of the total weight of washed coal. These percentages of misplaced material are converted into percentages of the feed and their sum subtracted from 100 to give the Anderson Efficiency, e.g.,

Weight misplaced in Washed Coal - %
= 1.6% of 88.5% (Yield of Washed Coal) = 1.42
Weight misplaced in Refuse - %
= 7.4% of 11.5% (Yield of Refuse) = 0.85
Total weight misplaced - % = 2.27
Anderson Efficiency = 100 - 2.27 = 97.7%

Zero efficiency has been defined by Anderson as that when no effective separation has been accomplished, i.e., when the specific gravity composition of the cleaned coal and refuse products is the same. Float-sink data as shown in Table VI have been used by Anderson to illustrate that the specific gravity composition of both washed coal and refuse are the same when the Anderson Efficiency is zero.

The definition of 100% efficiency has been offered by Anderson as being that when there is no sink material in the washed coal with a

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* The above example was chosen because the specific gravity of separation was 1.80 which was the specific gravity of one of the float-sink baths employed. If the specific gravity of separation does not happen to have the same value as that of one of the float-sink liquids, (which is the usual case) the amounts of misplaced material are found by interpolation.

TABLE VI

Float-Sink Data Illustrating Anderson Zero Efficiency

Specific Gravity Fraction	Washed Coal Weight %	Refuse Weight %
Float 1.30	25.0	25.0
1.30 - 1.40	35.0	35.0
1.40 - 1.50	8.0	8.0
1.50 - 1.60	5.0	5.0
1.60 - 1.70	4.0	4.0
1.70 - 1.80	2.0	2.0
1.80 - 2.00	1.0	1.0
Sinks 2.00	20.0	20.0
	100.0	100.0

specific gravity higher than the specific gravity of separation and no float in the refuse with a specific gravity lower than the specific gravity of separation. The data in Table VII have been presented by Anderson to illustrate this definition of 100% efficiency. The specific gravity of separation in this case was 1.60.

A point which the coal-cleaning authorities who contributed to a written discussion of Anderson's paper (29) seem to have overlooked is that the Anderson Efficiency does not use the basis for zero efficiency which Anderson has specified. The efficiency has been defined as being zero when the float and sink analyses of the refuse and cleaned coal, and therefore, of the feed are the same; in other words, when

TABLE VII

Float-Sink Data Illustrating 100% Anderson Efficiency

Specific Gravity Fraction	Washed Coal Weight %	Refuse Weight %
Float 1.30	90.0	0.0
1.30 - 1.40	5.0	0.0
1.40 - 1.50	4.0	0.0
1.50 - 1.60	1.0	0.0
1.60 - 1.70	0.0	1.0
1.70 - 1.80	0.0	4.0
1.80 - 2.00	0.0	5.0
Sinks 2.00	0.0	90.0

the coal comes out of the cleaner in the same condition as it went in, the efficiency is zero. However, this definition of zero efficiency is lost sight of in the course of the efficiency calculations. Here is an example illustrating this point. Table VIII shows the data from which Anderson has calculated 55% efficiency (1). The yield of washed

TABLE VIII

Float-Sink Data Illustrating 55% Anderson Efficiency
Yield of Washed Coal = 50%

Specific Gravity Fraction	Washed Coal Weight %	Refuse Weight %
Float 1.30	1.0	0.0
1.30 - 1.40	6.0	2.0
1.40 - 1.50	10.0	5.0
1.50 - 1.60	76.0	76.0
1.60 - 1.80	5.0	10.0
1.80 - 2.00	2.0	6.0
Sinks 2.00	0.0	1.0

coal is given as 50% and the specific gravity of separation as found from the distribution curve is 1.55. The amounts of misplaced material in both washed coal and refuse are found to be 22.5%, making a total of 45%. The Anderson efficiency for this separation is therefore 100 - 45 = 55%. Anderson, has stated that, "if for some ridiculous reason, a cleaning process should deliver a refuse product containing more float than the washed coal product, a true separation, nevertheless, could be effected by the cleaning equipment, but the efficiencies of separation would be less than 50%". In other words, if the washed coal product comes out of the equipment dirtier than when it entered, the efficiency is less than 50%. An illustration of separation with an efficiency of this order is given by Anderson: the specific gravity composition of the washed coal and refuse products shown in Table VIII are switched to give the distribution of material shown in Table IX,

TABLE IX

Float-Sink Data Illustrating 45% Anderson Efficiency
Yield of Washed Coal = 50%

Specific Gravity Fraction	Washed Coal Weight %	Refuse Weight %
Float 1.30	0.0	1.0
1.30 - 1.40	2.0	6.0
1.40 - 1.50	5.0	10.0
1.50 - 1.60	76.0	76.0
1.60 - 1.80	10.0	5.0
1.80 - 2.00	6.0	2.0
Sinks 2.00	1.0	0.0

i.e., what was the washed coal is now the refuse and vice versa. The Anderson Efficiency for this separation is 45%. It seems ridiculous that a process giving a washed coal product which is dirtier than the feed should be assigned a positive efficiency, especially since zero efficiency has been defined by Anderson as that when the feed coal goes through the equipment unchanged. In fairness to Anderson it should be pointed out that such a separation is probably never met with in practice. However, the fact still remains that this weakness does exist and although the percentage of misplaced material (which Cerchar calls the "tramp error") or its complement when subtracted from 100 is a useful criterion for judging washery performance, this complement should not be represented as an efficiency.

PROBABLE ERROR (3, 42)

This method, which was proposed by Terra (42), is also based on the distribution curve. The probable error is the numerical value of half of the difference between the specific gravities at which the distribution curve crosses the ordinates representing 25 and 75 % of the feed going to washed coal.

The probable error for the cyclone separation of Experiment No. 40 is found from the distribution curve in Figure 5. The specific gravity value at the 25% point is 1.765 and that at the 75% point is 1.625. The difference between these values is 0.140 and half this difference is 0.070 which is the probable error.

This method has been adopted by the French Centre d'Etudes et Recherches des Charbonnages de France (Cerchar) as a means of showing the sharpness of separation in place of the error area.

DRIESSEN ERROR AREA (18)

Driessen plotted the distribution curve using a fixed scale of 1 cm. = 2% of weight on the ordinate and 1 cm. = 0.10 specific gravity unit on the abscissa. The sum of the shaded areas, AHK and KDE, shown in Figure 5, are defined as the error area expressed in square centimeters. The upper area, AHK, gives a measure of the amount of clean coal which has been discarded with the refuse and the lower area, KDE, gives a measure of the refuse which has gone into the washed coal. The sum of these two areas is the Error Area for the washing process. The main disadvantage of the Error Area is that a planimeter is required to determine the areas. Another objection is that it does not express the sharpness of separation as a percentage.

The authorities on coal preparation both in Europe and on this continent have accepted the Error Area which uses the fixed centimeter scale proposed by Driessen as a measure of coal washery performance. A much more flexible and simple method would be that proposed by Van der Walt (45), of expressing the Error Area in terms of (specific gravity x weight percent) units. Any scale could then be used to plot the distribution curve.

AREA EFFICIENCY

It would be advantageous if the Error Area could be expressed as a percentage efficiency rather than an area in square centimeters, since a percentage is much more readily understood than the number of square centimeters which must be compared with some standard reference area. As a result of the studies during the present investigation a new method of expressing the Error Area as an efficiency of separation is proposed. Using the distribution curve shown in Figure 5 as an example, the Area Efficiency would be:

$$\frac{(\text{Area AHKB} - \text{Area AHK}) + (\text{Area KFED} - \text{Area KED})}{\text{Area AHKB} + \text{Area KFED}} \times 100\%$$

A perfect separation according to specific gravity would give 100% separation efficiency by this method since the Areas AHK and KED would approach zero as the slope of the distribution curve approached the vertical at the specific gravity of separation. In other words, when the error area is zero the Area Efficiency is 100%. This method has the advantage that any scale can be used for plotting the distribution curve and that the degree of separation is shown by a percentage efficiency rather than an area.

This efficiency is directly proportional to the Error Area as is shown in Fig. 7 in which the area efficiencies have been plotted against the corresponding error areas for some of the cyclone separations obtained in this investigation. It is therefore a simple matter to convert from Area Efficiency to Error Area or vice versa providing that the lightest and heaviest portions of the feed coal are assumed to have specific gravities of 1.25 and 2.60 respectively.

For these conditions Area Efficiency % = $(100 - 0.39\ E)\%$

where E = Error Area in sq. cm.

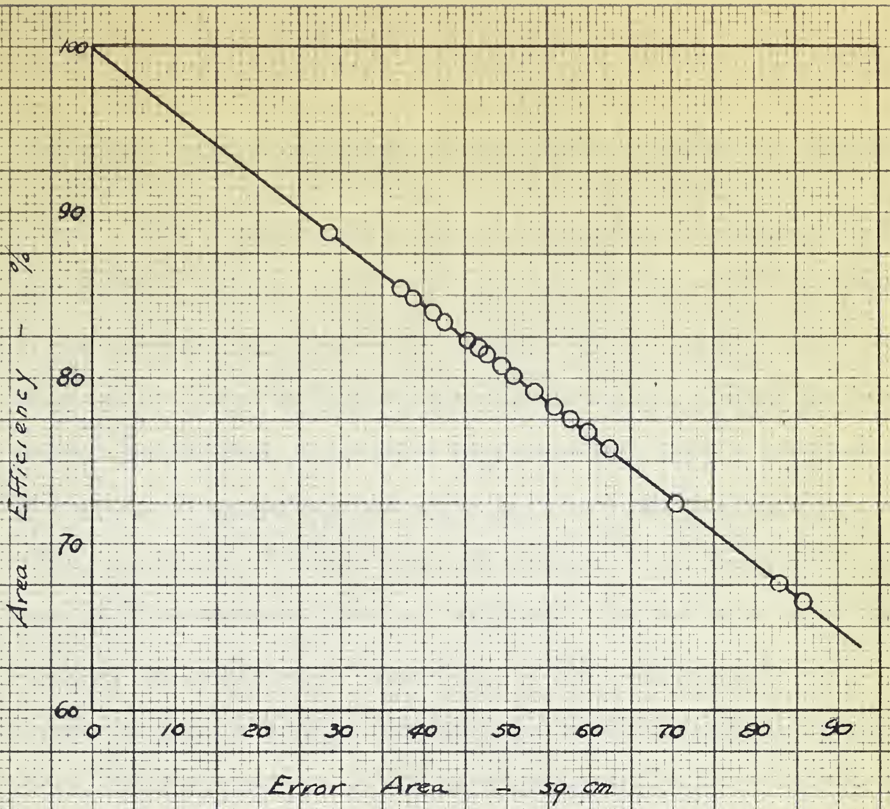

Fig. 7 Plot showing straight-line relationship between Area Efficiency and Error Area.

DISCUSSION OF VARIOUS METHODS OF EVALUATING COAL-WASHING PERFORMANCE

The foregoing efficiencies and formulas represent some of the numerous attempts which have been made to represent the performance of coal-cleaning equipment by a single factor. As has been pointed out, all have some merits and some deficiencies. During the last few years, Cerchar coal preparation engineers have made a detailed study of methods of expressing the efficiency of coal-cleaning equipment. Their conclusions (3) were that the problem of evaluating the performance of a coal-cleaning unit is a difficult one, and that it is impossible to judge the performance adequately by means of a single term. The Cerchar engineers suggest that the most useful methods are the probable error, distribution curves, "tramp" error, and loss of organic efficiency. The "tramp" error is the percentage of misplaced material which has been mentioned previously. The Organic Efficiency is the same as the Fraser-Yancey Efficiency. The loss of Organic Efficiency is the difference resulting when the Fraser-Yancey Efficiency is subtracted from one hundred.

In this investigation, the Probable Error, Error Area, Area Efficiency, Anderson Efficiency and Fraser-Yancey Efficiency have been used to evaluate the results of the cyclone experiments.

VI OBJECT AND SCOPE OF PRESENT INVESTIGATION

The literature review of coal-cleaning methods showed that none of the processes were entirely satisfactory for cleaning fine coal, i.e., coal below 1/4-inch or 1/8-inch in size. Of all the coal-washers reviewed, the cyclone washer seemed to give the most promise as a fine coal cleaner. Consequently, the Research Council of Alberta began studies on the cleaning of fine coal with a three-inch D.S.M. Cyclone.

The literature survey on the cyclone washer demonstrated that, although considerable work had been done by other investigators, data were lacking on the influence of several important operating variables on the performance of the cyclone washer. Accordingly, the first phase of the present investigation was concerned with a study of the effects of pulp ratio of the slurry, specific gravity composition of the feed and size composition of the feed.

The second phase of the present investigation was concerned with the evaluation of coal-washery performance. As has already been pointed out in the preceding section, many methods of assessing the quality of coal-cleaning are in use. However, no agreement seems to exist between any of these various means of judging coal-washing performance. In addition, there is lack of agreement among the leading coal-preparation authorities as to the influence of the specific gravity of separation on the Error Area and Probable Error. Perhaps the major reason for the existence of such a condition is that sufficient data on coal-cleaning separations have not been published. Therefore, the object in the second part of this study was to obtain such data on cyclone separations and to examine these critically so that some insight

could be gained into the behaviour of the various means of measuring the efficiency of coal-cleaning. It was proposed to do this by determining the influence of the variables of cyclone geometry and specific gravity of the medium on the specific gravity of separation, Error Area, Probable Error, Fraser-Yancey Efficiency and Anderson Efficiency.

VII EXPERIMENTAL EQUIPMENT AND PROCEDURE

DESCRIPTION OF D.S.M. CYCLONE

Fig. 8 shows the design of the D.S.M. Cyclone used in the experiments conducted for this investigation. This diagram shows the simple construction of the cyclone. The conical section is six inches long and has a maximum inner diameter of three inches. Above the conical section is a cylindrical section called the feed chamber and directly above this component is the vortex finder and overflow chamber. The vortex finder consists of a hollow-tube set in the center of a circular plate. At the left of the diagram can be seen the tapered feed inlet which is joined tangentially to the cylindrical feed chamber. Removable shims can be inserted to adjust the size of the feed inlet but these were not used as it was desired to make all tests with the greatest throughput possible. At the apex of the cone is a rubber valve which is merely a cylindrical rubber ring held in place by a constriction ring and an adjustable tailpiece. The tailpiece and the lower part of the cone are threaded, so that turning the tailpiece pushes the constriction ring against the rubber valve, thereby adjusting the diameter of the opening in its center. This valve regulates the refuse discharge from the bottom of the cyclone. The diameter of the opening can be varied from a maximum of 0.78 inches to as small as desired.

The feed slurry enters through the feed inlet tangentially to the cylindrical feed chamber. The slurry rotates in the cone so that a vortex is formed and a vertical air column is maintained in the central part of the cyclone. According to Driessen (18) a state of

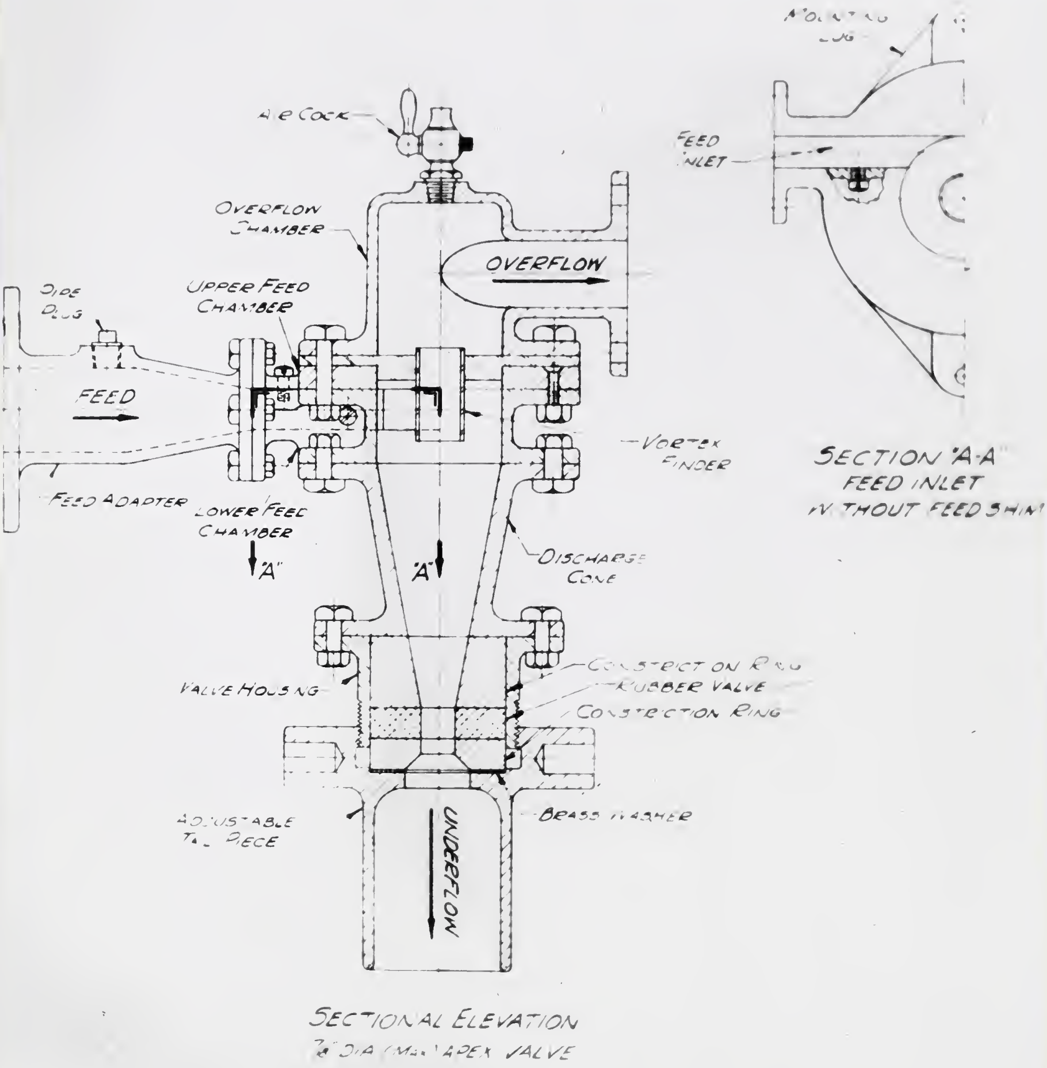
AIR COCK
OVERFLOW CHAMBER
OVERFLOW
PIPE PLUG
UPPER FEED CHAMBER
FEED
FEED ADAPTER
LOWER FEED CHAMBER
"A"
"A"
VORTEX FINDER
DISCHARGE CONE
CONSTRICTION RING
RUBBER VALVE
CONSTRICTION RING
VALVE HOUSING
BRASS WASHER
ADJUSTABLE TAIL PIECE
UNDERFLOW
SECTIONAL ELEVATION
7/8" DIA (MAX) APEX VALVE
MOUNTING LUG
FEED INLET
SECTION "A-A"
FEED INLET
WITHOUT FEED SHIM

Fig. 8 Design of D.S.M. Cyclone.

3" diameter. 20° Cone.

equilibrium appears to exist between the centrifugal force working on the small suspension particles and the flow of the liquid which acts in the opposite direction. The suspension particles which are introduced into the cyclone together with the raw fine coal, are forced towards the wall and move down towards the apex. Here some of the particles leave the cyclone while others rise in the central vortex and either leave the cyclone through the overflow at the top or are again forced towards the wall to repeat the above cycle. In this way, some of the suspension particles are circulating in the cyclone, so that the concentration and therefore the specific gravity of the suspension is higher in the cyclone than it is at either the feed inlet or overflow outlet.

DESCRIPTION OF EXPERIMENTAL EQUIPMENT

The experimental set-up is shown in Figs. 9 and 10. Batch tests only were made since neither the equipment nor facilities for continuous operation were available. The cyclone was installed over a sixty-gallon mixing tank (a) which was provided with baffles and a two inch bottom outlet. A one-half horsepower "Lightnin" mixer (b) provided efficient mixing of the slurry. A one-inch centrifugal sand pump (c) drew the feed slurry from the tank and delivered it to the feed inlet of the cyclone (d). Overflow and underflow from the cyclone were returned to the mixing tank. However, provision was made for collecting and weighing timed samples of the overflow and underflow streams by simultaneously directing the flows into two weighing tanks. The trough (f) carried the underflow stream containing the refuse into the weighing tank (g) and the overflow stream containing the clean coal

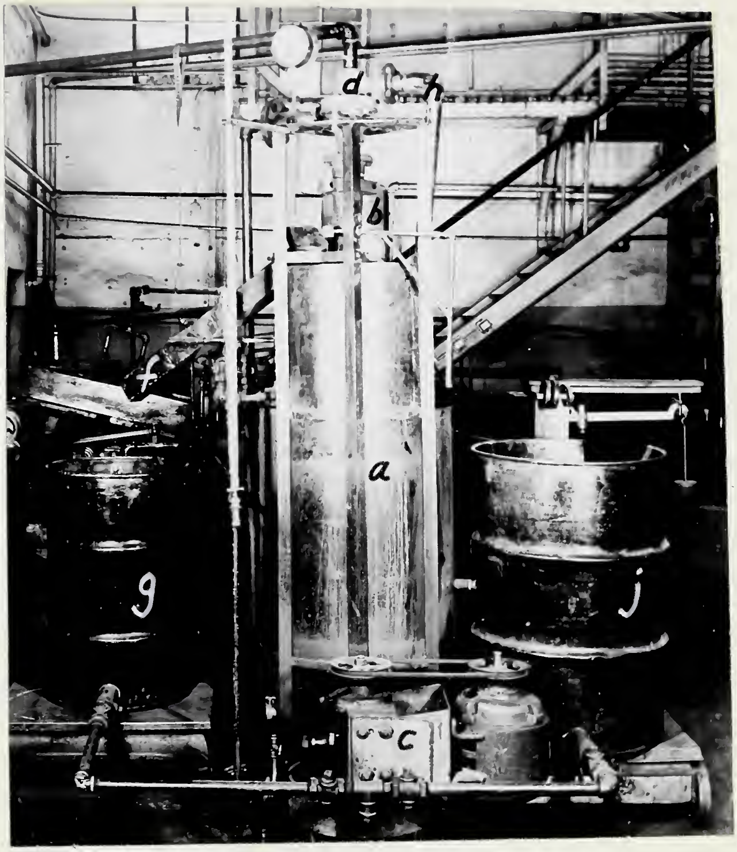

Fig. 9 Experimental set-up of D.S.M. cyclone coal-washing equipment.

travelled through the overflow pipe (h) into the weighing tank (j). The refuse trough and overflow pipe were joined so that samples of underflow and overflow could be taken simultaneously.

EXPERIMENTAL PROCEDURE

The procedure adopted for a coal cleaning tests was as follows: The suspension of magnetite and water was brought to the required specific gravity and a quantity of fine coal (-10 + 100 mesh) was added; the amount of coal to be added depended upon the desired pulp ratio*. The pump was then started, the valve to the cyclone feed inlet opened and the inlet valve to the pump regulated until the required pressure was indicated on the inlet pressure gauge of the cyclone. When the operator was ready to collect samples of each stream, the flows were simultaneously directed into the two weighing tanks for a timed interval. At the end of this time the streams were returned to the mixing tank.

Initial Magnetite Recovery Procedure

The first method used for recovering the magnetite medium was to pump the slurry containing the magnetite, washed coal, and water through a laboratory-size belt-type Dings magnetic separator. (k in Fig. 10) The belt was turned by means of the motor (w) and a chain and sprocket arrangement. The magnetite was carried by the belt past the influence of the separator magnets and dropped through a demagnetizing coil (m) through the pipe (n) into a pail (o). The washed

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*The term "pulp ratio" is defined here as the ratio of the weight of magnetite and water suspension to the weight of coal. A pulp ratio of six to one was used for most of the experiments in this investigation.

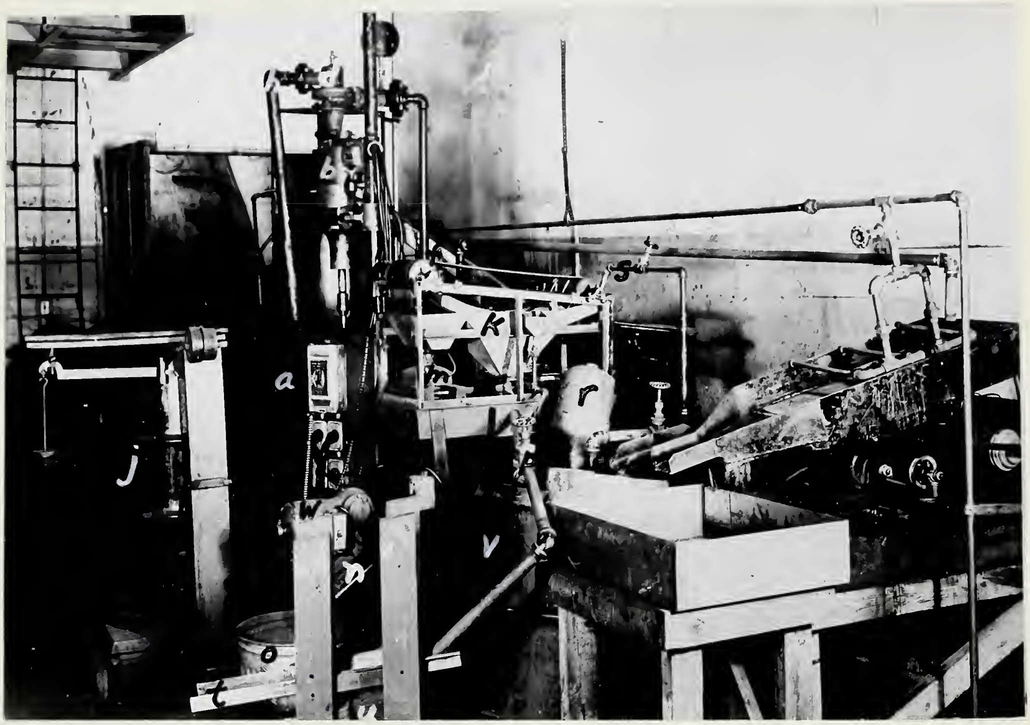
d
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Fig. 10 Another view of D.S.M. cyclone coal-washing equipment showing magnetic separator and 100-mesh shaker screen.

coal dropped to the bottom of the separator through the pipe (p) into the tank (v). The "Lightnin" mixer (r) was employed to keep the coal in suspension. This slurry was then pumped through the pipe (s) to the feed entrance of the magnetic separator for another pass through it to remove the remaining magnetite. The coal was again removed from the separator through the pipe (p) and routed through a brass trough (t) which was placed over an electromagnet (u). This electromagnet was designed to pick up any remaining magnetite in the slurry. The coal was caught in a 100-mesh dewatering screen (not shown in Fig. 10) placed at the end of the trough. The above procedure was repeated for the underflow slurry containing the refuse product. The washed coal and refuse products were then dried, weighed, and sampled for ash and float-sink analysis.

Final Magnetite Recovery Procedure

After several cleaning tests had been conducted, using the above magnetite recovery procedure, it was found that considerable size degradation of the coal occurred. As a result of this size degradation, the ash content of the feed as calculated from the products varied from 14 to 17%, whereas, the ash content of the original raw feed was 19%. Because of this factor it was almost impossible to compare the cleaning results from the various experiments. The size degradation was due to the lengthy immersion time of the coal in the circuit, coupled with the pumping and mixing necessary in the magnetite recovery process. The immersion time of some of the coal was as much as three hours because of the limited size of the magnetic separator

and the necessity of two passes for each product through the equipment.

Because the calculated ash content of the feed varied so widely when the magnetite was removed in the above manner a different method of separating the magnetite from the washed coal and refuse was finally adopted. The samples in the first experiments contained from 20 to 30 lbs. of coal and were collected in 30 to 45 seconds. In the later experiments the sampling time was cut to approximately 15 seconds so that samples of slurry containing approximately 10 lbs. of coal were collected. The magnetite was rinsed off the washed coal and refuse by spraying with water on a 100-mesh screen. In this manner, the immersion time was cut to 15 or 20 minutes and the need for excessive pumping and mixing of the slurry was circumvented. This procedure for removing magnetite from the products was used for all of the experiments for which data are reported in this thesis. Considerable size degradation still occurred with the revised magnetite recovery procedure, since the ash of the feed as calculated from the products was approximately 17% as compared with 19% for the ash content of the raw feed. However, this calculated ash figure was reasonably constant so that the various separations could be compared.

OPERATING VARIABLES INVESTIGATED

Some of the variables which may influence the operation of a cyclone washer are inlet feed opening, vortex finder (overflow) diameter, inlet feed pressure, underflow apex diameter, specific gravity of the medium, pulp ratio of the slurry, size composition of the feed coal, and specific gravity composition of the feed coal. Geer and Yancey (25) have shown that the size of the inlet feed opening

has little influence on cyclone performance. For this reason and because maximum throughput was desired, the largest inlet feed area of 0.78 square inches was employed for the present experiments. Further, it was considered that the feed inlet and overflow opening should have approximately the same area for most efficient operation, since most of the feed slurry goes out through the overflow. Therefore, a vortex finder diameter of 1.03 inches and area of 0.83 square inches was selected for all the experiments. The maximum inlet feed pressure that could be maintained by the feed pump was 13.5 p.s.i.g. This pressure was used for all the experiments because the work of Geer and Yancey had indicated that increased efficiency was given by higher pressures. A pulp ratio of six to one was used for all the experiments except those in which the influence of pulp ratio on the performance of the cyclone was being studied. The throughput of raw coal at an inlet feed pressure of 13.5 p.s.i.g. and pulp ratio of six to one through the three-inch diameter cyclone was 1.2 tons per hour.

The influence on cyclone performance of the variables of pulp ratio of the feed, specific gravity composition of the feed, and particle size of the feed were studied in the first phase of the experiments. In the second phase of the investigation, a study was made of the influence of the size of the cyclone underflow-opening and specific gravity of the medium on the specific gravity of separation, Probable Error, Error Area, Fraser-Yancey Efficiency and Anderson Efficiency.

UNDERFLOW OPENING DIAMETER AND SPECIFIC GRAVITIES OF MAGNETITE MEDIUM USED FOR EXPERIMENTS

Cerchar investigators (4) have reported that the best cyclone operating results were given when the overflow and underflow exit diameters were approximately equal and the specific gravity of the medium approached the value of the specific gravity of separation. This means that, if it were desired to perform a separation at a specific gravity in the region of 1.60 - 1.70 at maximum separation efficiency, a suspension of the same order of specific gravity would be required. It was believed that, in this country, it would likely be more economical and practical to sacrifice a slight sharpness of separation for reduced costs of medium and medium recovery by using suspensions with as low a specific gravity as possible. In order to utilize these suspensions of lower specific gravity, the ratios of underflow to overflow exit diameters had to be much less than the ratio of approximately one to one recommended by the Cerchar investigators. The underflow opening diameter was varied from 0.78 to 0.58 inches while the overflow exit diameter was held constant at 1.03 inches. Thus, the maximum ratio of underflow to overflow diameter was 0.76 and the minimum 0.56; the corresponding area ratios were 0.58 and 0.31. By employing underflow openings smaller than the overflow opening, use was made of one of the advantages of the cyclone washer over other heavy-media methods of cleaning, i.e., the separations were accomplished at much higher specific gravities than the specific gravities of the suspension used.

TYPES OF UNDERFLOW DISCHARGE

The minimum underflow opening diameter that could be used was determined from preliminary experiments to be 0.55 inches since any opening smaller than this did not produce a spray discharge. When an underflow opening of less than 0.55 inches was used under the experimental conditions as outlined in preceding sections, a "rope" type of discharge was produced. The difference between a "rope" and a "spray" discharge was easily discernible during operation of the cyclone. When a "spray" discharge was being maintained, the sound of air rushing through the apex of the cone was clearly audible, the inlet pressure gauge remained steady and the underflow discharge was in the form of a vortex which sprayed around the inner edge of the tailpiece. With a "rope" discharge there was no rush of air, the pressure gauge was often unsteady, and the underflow discharge had the appearance of a rope. A rope discharge was undesirable since with it excessive underflow product was carried over into the overflow.

COAL USED

The coal used in this investigation was a medium-volatile bituminous-rank coal obtained through the courtesy of Cadomin Coal Co. Ltd. The coal was crushed and screened to give a sized product of 10- to 100-mesh. Coarse material could not be used in a three-inch cyclone and 100 mesh was considered to be the finest size that could be recovered on the dewatering screen. This size range is greater than that used by Geer and Yancey (25) (14- to 35-mesh) but it was decided to extend the lower limit to determine whether or not cleaning could be accomplished on the finer sizes.

The same feed coal was used for most of the runs in order to keep the number of variables to a minimum. However, various types of feed were made up from this coal by blending with it a portion of the 1.40-1.80 specific gravity fraction or the material heavier than 1.80. This gave the variable feed which is encountered in actual commercial cleaning plant operation.

MEDIUM USED

The medium used was a suspension of finely-ground magnetite and water. The magnetite, designated as Magnetite B, was obtained from the Foote Mineral Co., Philadephia, Pa. The size specification given for the material was that 90-95% passed through a 325 mesh screen. A screen analysis showed that practically none of the magnetite was retained on a 150 mesh and 93.3% went through a 325 mesh screen. Magnetite was chosen for the suspension medium because it was thought that magnetic separation of the magnetite from the coal might be the answer to the medium-recovery problem. In addition, since magnetite has a high density (4.6 - 4.7) the amount required to give the required specific gravity of suspension is small and the "viscosity" of the medium is lower than would be the case with most other materials.

VIII RESULTS AND INTERPRETATION OF RESULTS

A. INFLUENCE OF VARIOUS OPERATING VARIABLES ON CYCLONE PERFORMANCE

In this first phase of the investigation an attempt was made to determine the influence on the cyclone performance of those operating variables on which little or no published data were available. The efficacy of the cleaning accomplished in each experiment was assessed by an appraisal of the yields and ash contents of the products, Fraser-Yancey Efficiency, Probable Error, Error Area and the amount of misplaced material.

(1) PULP RATIO OF THE SLURRY

The experiments to determine the influence of pulp ratio of the slurry were conducted under the following constant conditions: specific gravity of magnetite medium 1.30, inlet feed pressure 13.5 p.s.i.g., inlet feed area 0.78 square inches, overflow vortex finder diameter 1.03 inches, and underflow apex diameter 0.59 inches; the ratio of underflow to overflow-opening area was 0.33. The only variable in this series of experiments was therefore the pulp ratio of the slurry which has previously been defined as the ratio of the weight of water and magnetite suspension to the weight of coal added. The pulp ratio was varied from three-to-one to eight-to-one for this phase of the investigation. The data given by these cyclone separations are shown in Table X.

The best separations resulted from use of the eight-to-one pulp ratio. This was what might have been expected, since the "viscosity" of this slurry was lower than that of the others used in this series of

experiments due to the smaller amount of coal added. As the pulp ratio was decreased or in other words, as greater quantities of coal were added, the sharpness of separation deteriorated; this is shown by both the probable errors and the error areas. The only unacceptable separation was that due to the three-to-one pulp ratio with a probable error of 0.130 and error area of 85.7. The Fraser-Yancey Efficiency also decreased as the pulp ratio decreased with the only unacceptable efficiency of 93.4% again being given by the three-to-one pulp ratio.

TABLE X

Data for Cyclone Separations Illustrating Influence of Pulp Ratio on Cyclone Washing Performance

Test Number	46	47	44	45
Pulp Ratio	8 to 1	6 to 1	4 to 1	3 to 1
Yield of Washed Coal %	82.0	82.2	84.2	79.4
Ash Content of Washed Coal %	9.6	9.8	10.4	10.0
Ash Content of Refuse %	52.6	52.8	53.9	45.2
Calculated Ash Content of Feed %	17.2	17.5	17.3	17.2
Specific Gravity of Separation	1.65	1.67	1.69	1.62
Probable Error	.066	.072	.092	.130
Error Area sq.cm.	46.6	52.7	70.5	85.7
Fraser-Yancey Efficiency %	98.3	97.6	97.2	93.4
Misplaced Material %	3.7	5.2	6.0	9.2
Area Efficiency %	81.9	79.4	72.5	66.6

These results indicated that as long as the pulp ratio was not allowed to become less than four-to-one, satisfactory operation could be achieved. The yields of washed coal varied from 82.0 to 84.2% and the ash contents of the washed coal varied from 9.6 to 10.4%. In other words, fluctuations in feed rates would not greatly affect cyclone performance as long as overloading was avoided.

Van der Walt's data (45) showed that pulp ratios as low as three-to-one did not appreciably affect the quality of the separations. However, the diameter of the underflow opening of the cyclone used by Van der Walt was almost the same as that of the overflow vortex finder, (1.50 inches and 1.88 inches respectively). Under these conditions it is likely that the so-called "viscosity" effects in the lower conical section of the cyclone were less in Van der Walt's experiments than was the case for the cyclone used in the present investigation which utilized a much lower ratio of underflow to overflow-opening area (0.33 as compared with 0.64).

(2) SPECIFIC GRAVITY COMPOSITION OF THE FEED

A series of experiments was conducted with feeds having various specific gravity compositions in order to discover whether the specific gravity composition of the feed coal had any effect on cyclone performance. It was desired to utilize feeds which differed only in the percentage of coal present in the several density fractions, but which had, as nearly as possible, the same characteristics such as particle size, shape, etc. To attain this end, the cyclone was used to wash Cadomin 10- to 100-mesh coal at different specific gravities of separation. The products were blended with raw Cadomin 10- to 100-mesh coal to give the various feeds. So far as can be ascertained, no attempt of this nature has been made heretofore. Other workers

have generally added foreign material such as sand to the raw coal or used different types of coal to obtain feeds with dissimilar density compositions.

An example of the ± 0.10 specific gravity distribution curve for the calculated feed coal of Experiment No. 40 is presented in Fig. 11. This curve was proposed by Bird (6) to demonstrate the degree of difficulty of washing of a coal. It shows the percentage of the feed coal lying within a range of ± 0.10 of any specific gravity. The data for plotting the curve are obtained from the cumulative float versus specific gravity curve shown in Fig. 6, e.g., the cumulative float at 1.60 specific gravity is 77.1% whilst that at 1.80 is 85.7%. Therefore the difference between these two values - 8.6% - is the amount of material in the feed lying within ± 0.10 of 1.70 specific gravity (i.e. between 1.60 and 1.80). This value of 8.6 is plotted at 1.70 specific gravity and the points for the remainder of the curve are found in a similar manner.

Bird's method presupposes that the degree of washing difficulty of coal is dependent upon the amount of material near the specific gravity of separation. This seems to be a logical method of assessing the washability of coal; other things being equal, (particle size, shape, etc.) it seems reasonable to assume that the greater the percentage of material in the feed near the density at which the separation is to be made, the more difficult will be the separation. The scale of washing difficulty proposed by Bird is shown in Table XI

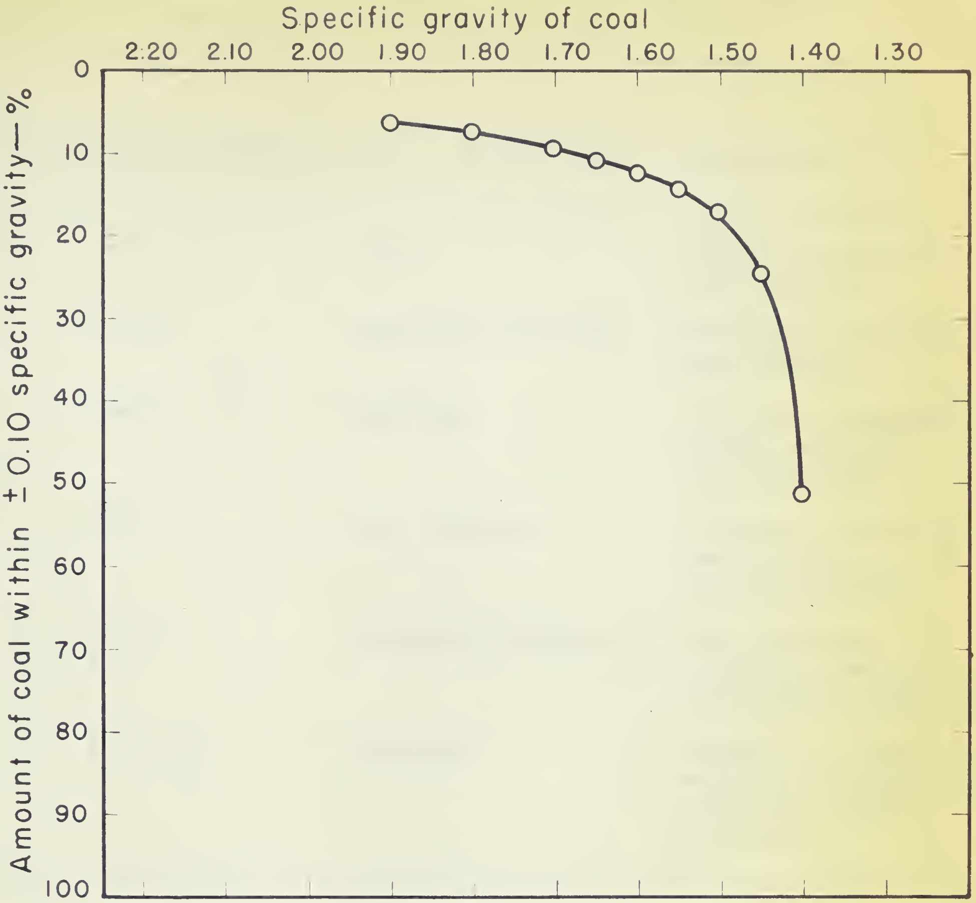

Fig. 11 ± 0.10 Specific gravity curve for feed coal used in experiment No. 40

TABLE XI

Scale of Washing Difficulty Based on ± 0.10 Specific Gravity Percentage Values Proposed by Bird (6)

± 0.10 Specific Gravity %	Degree of Difficulty	Preparation
0-7	Simple	Almost any process, high tonnages
7-10	Moderately difficult	Efficient processes; high tonnages
10-15	Difficult	Efficient processes; medium tonnages, good operation
15-20	Very difficult	Efficient processes; low tonnages; expert operation
20-25	Exceedingly difficult	Very efficient processes; low tonages; expert operation
Above 25	Formidable	Limited to a few exceptionally efficient processes; expert operation

The data for the series of experiments for this phase of the investigation are shown in Table XII. These experiments were all made under the following constant conditions; specific gravity of magnetite medium, 1.30, pulp ratio 6 to 1, inlet feed pressure of 13.5 p.s.i.g., inlet feed area 0.78 square inches, overflow vortex finder diameter 1.03 inches, and underflow opening diameter of 0.66 inches. The only variable was the specific gravity composition of the feed.

TABLE XII

Data for Cyclone Separations Illustrating Influence of Specific Gravity Composition of the Feed on Cyclone Washing Performance

Experiment Number	49	53	50	51
± 0.10 Specific Gravity %	9.8	14.6	17.6	23.6
Yield of Washed Coal &	79.7	73.1	68.1	75.8
Ash Content of Washed Coal %	9.1	10.2	8.9	10.4
Ash Content of Refuse %	51.1	50.9	48.5	39.6
Calculated Ash Content of Feed %	17.6	21.6	21.6	17.5
Specific Gravity of Separation	1.61	1.62	1.58	1.59
Probable Error	0.073	0.070	0.067	0.039
Error Area sq.cm.	46.0	41.2	41.0	28.5
Fraser-Yancey Efficiency %	97.5	96.8	96.2	96.1
Misplaced Material %	4.0	5.2	6.2	4.5

The unblended feed of Experiment No. 49 gave the lowest ± 0.10 specific gravity value of 9.8% and, therefore, under Bird's classification is a moderately difficult coal to wash. The feed for Experiment No. 53 was a more difficult coal to wash with a ± 0.10 specific gravity value of 14.6%, whilst the coal used for Experiment No. 50 was classed as a very difficult washing problem with a ± 0.10 value of 17.6%. The feed for Experiment No. 50 with a ± 0.10 value of 23.6 was classed as an exceedingly difficult coal to wash. These

± 0.10 specific gravity values were all found from the ± 0.10 specific gravity curve for each feed coal at the actual specific gravity of separation. It will be noted that, although the calculated ash contents of the feeds for Experiment Nos. 49 and 51 were almost identical at 17.6 and 17.5% respectively, the degree of washing difficulty was quite different with ± 0.10 values of 9.8 and 23.6% respectively. The feeds of Experiment Nos. 50 and 53 had identical ash contents of 21.6% but different ± 0.10 values of 17.6 and 14.6% respectively; the difference between these two values was probably not great enough to have any effect on the washing results.

Further examination of the data in Table XII shows that the sharpness of separation, as measured by the error areas and probable errors did not deteriorate with increasing difficulty of washing, i.e. the probable errors and error areas for Experiments Nos. 49, 53 and 50 were approximately equal. The lowest probable error and error area were given by the separation achieved in Experiment No. 51. A probable explanation for these results is that this sharpest separation, obtained with the feed which was presumably the most difficult coal to wash, was due to the influence of particle size. As has been stated previously, the feed coals for all of the experiments in this series except that for Experiment No. 49 consisted of raw coal (such as that used for Experiment No. 49) to which was added coal on which previous separations had been made with the cyclone washer. A certain amount of sizing occurred in the cyclone, with the coarser material tending to go to the underflow. Only a small amount of high-ash refuse material was added to the raw coal to make up the feeds for Experiment Nos. 50 and 53;

these amounts were probably too small to alter the over-all size composition of the feed. However, for the feed used in Experiment No. 51 a considerably larger amount of coal having an intermediate specific gravity in the region of 1.40 - 1.80 was used for blending. It is likely, therefore, that this feed contained a larger proportion of coarse material than did the others in this series of experiments. This would account for the lower probable error and error area values achieved in this experiment, since the cyclone performs much sharper separations* on the coarser particles (+48 mesh) than it does on the finer particles (-48 mesh) of coal.

Despite this undesirable influence of particle size on the separations, the results demonstrated that the cyclone was surprisingly adaptable to changes in the washing difficulty of the feed coal. This was shown by the ash contents of the washed coal products which only varied from 9.1 to 10.4%. The ability to yield a product with a specific ash content is important in coal preparation, since a washed coal with a guaranteed minimum ash content is usually required. In addition, the Fraser-Yancey efficiencies for the separations in this series of experiments were satisfactory showing that there was no excessive loss of clean coal.

(3) PARTICLE SIZE OF THE FEED

Experiment No. 47 was conducted to investigate the influence of particle size of the feed coal on the cleaning effected by the cyclone washer. This experiment was conducted with a 1.30 specific gravity medium and a 0.59 inch underflow opening diameter so that the ratio of underflow to overflow-opening area was 0.33. All the other variables

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*See p. 89 for Influence of Particle Size.

were held constant at the same values as those employed for the experiments for which the data are presented in Table XIV. Screen analyses were made on the washed coal and refuse products and float-sink analyses were performed on each size fraction; from these, distribution-curve data were calculated. A summary of the data for this experiment is shown in Table XIII while the distribution curves for the various size fractions are shown in Fig. 12.

TABLE XIII

Summary of Results for Cyclone Experiment No. 47
10- to 100-Mesh Cadomin Coal

Data	Screen Size Mesh					
	-10+14	-14+28	-28+48	-48+65	-65+100	-10+100
Weight of Fraction (in terms of the Feed)%	19.3	38.2	27.5	8.7	6.3	100.0
Yield of Washed Coal %	75.1	81.0	85.8	86.9	88.2	82.2
Ash Content of Washed Coal %	9.9	8.4	9.5	10.3	11.8	9.8
Ash Content of Refuse %	20.3	51.2	53.8	58.4	63.2	52.6
Calc. Ash Content of Feed %	20.0	17.3	15.8	16.6	17.9	17.4
Specific Gravity of Separation	1.63	1.65	1.72	1.79	1.84	1.66
Probable Error	0.061	0.088	0.089	0.115	0.156	0.072
Error Area sq. cm.	44.4	61.2	64.3	75.5	84.2	52.7
Area Efficiency %	82.7	76.1	75.1	70.5	67.1	79.4
Fraser-Yancey Efficiency %	99.9	96.9	97.5	97.7	97.8	97.6
Misplaced material %	5.8	5.9	5.2	4.8	5.3	5.5
± 0.10 Specific Gravity %	14.8	8.7	5.7	5.8	4.1	8.3

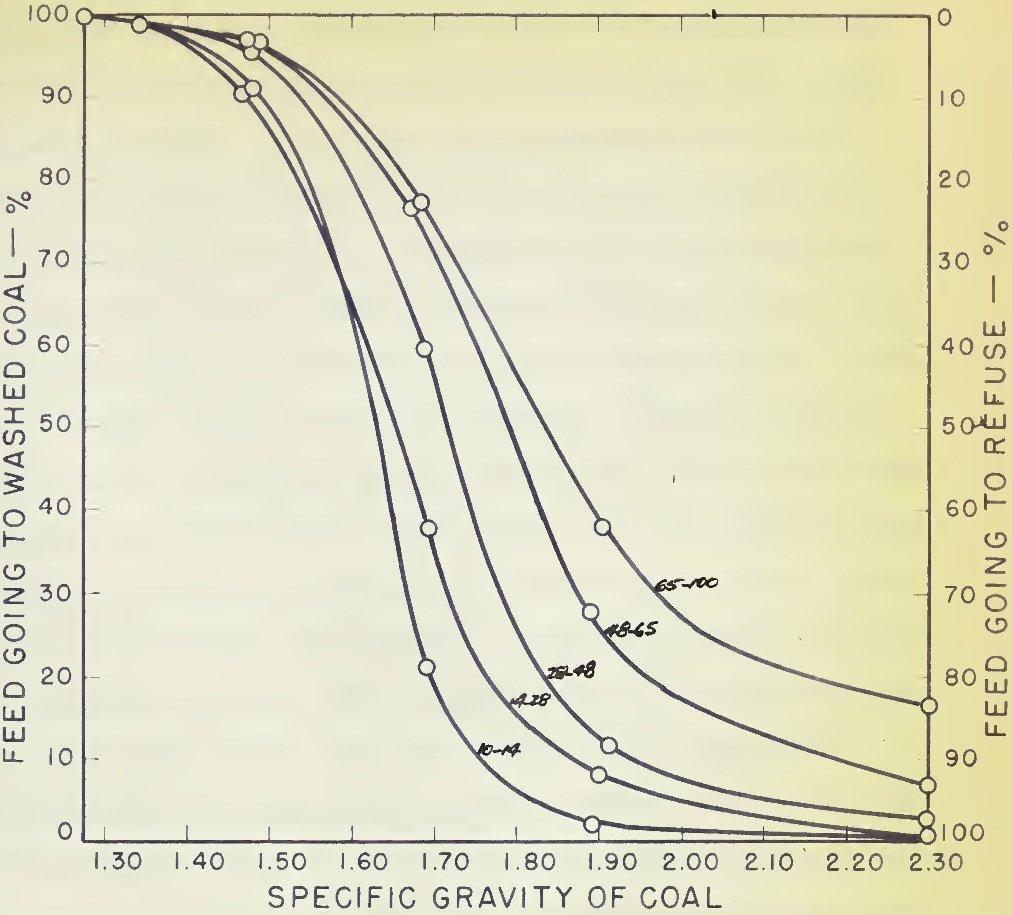

Fig.12 Distribution curves for various size fractions. Experiment No.47. Numbers on curves refer to screen sizes of fractions.

The distribution curves illustrate the manner in which the sharpness of separation deteriorated as the particle size decreased, the lowest probable error and error area being attained with the 10- to 14-mesh fraction. As the particle size decreased, the specific gravity of separation increased, the 10- to 14-mesh fraction being separated at 1.63 and the 65- to 100-mesh fraction at 1.84 specific gravity. These results verify the findings of Geer and Yancey (25), Van der Walt (45), and Burton (11) that the specific gravity of separation increases as the particle size decreases. However, the lower limit of coal that could be satisfactorily cleaned was not found to be the same as reported by these investigators. Geer and Yancey reported satisfactory cleaning on particles down to 65 mesh, but not on the coal in the 65- to 100-mesh size fraction. Van der Walt reported satisfactory cleaning on particles down to the 48-mesh size and unsatisfactory cleaning on sizes smaller than this. Burton, on the other hand, reported sharp separations with a probable error of 0.084 for the 120- to 200-mesh size range. In the experiment for the present investigation, satisfactory cleaning was accomplished on the 65- to 100-mesh fraction. Although the probable error of 0.156 was high as compared with that of 0.078 cited by Burton for this size range, the cleaning was considered to be good since the yield of washed coal for the fraction was 88.2% whilst the ash contents of the washed coal, refuse and feed were 11.8, 63.2 and 17.9% respectively; furthermore, the Fraser-Yancey Efficiency was 97.8% which indicated that the loss of clean coal was not too great.

It is interesting to note that Geer and Yancey and Van der Walt used underflow to overflow-exit area ratios of 0.86 and 0.75

respectively which were much larger than the ratio of 0.33 for Experiment No. 47. Cerchar (4) investigators have stated that the lowest probable errors are obtained when this ratio is slightly less than one and the density of the medium approaches the value of the specific gravity of separation. Better cleaning was accomplished on the 65- to 100-mesh coal in Experiment NO. 47 than that achieved on this size range by Geer and Yancey, and Van der Walt, even though the above mentioned conditions were met to a greater extent in their experiments than they were in the present investigation. Burton has not reported the cyclone underflow to overflow diameter ratio employed in the experiment to determine the influence of size composition of the feed. However, the underflow and overflow opening diameters for cyclone separations performed at similar specific gravities of separation were reported by Burton (11). The ratio of underflow to overflow-opening area for these experiments was 0.36 which is approximately the same as that used in Experiment No. 47 of the present investigation. If the assumption is correct that the underflow to overflow size ratio used by Burton for the particle size experiment was of this order, it would appear as though better cleaning on the finer sizes (minus 65 mesh) can be accomplished with a smaller ratio of underflow to overflow-opening area than that recommended by Cerchar investigators.

B. INFLUENCE OF SIZE OF UNDERFLOW OPENING AND SPECIFIC GRAVITY OF MEDIUM ON APPARENT EFFICIENCY OF CLEANING

Although the two operating valuables of size of underflow opening and specific gravity of the medium do not seem to be related yet they are so closely linked that it is difficult to discuss one without mentioning the other. This is because the specific gravity at which a separation is performed with the cyclone washer is influenced by both the size of the underflow opening and the specific gravity of the medium. With a given specific gravity of medium the specific gravity of separation is increased by reducing the size of the underflow opening and with a given underflow opening the specific gravity of separation is increased by raising the specific gravity of the medium. Consequently, these two most important operating variables are discussed together. In the following subsections, the influence of the operating variables of size of underflow opening and specific gravity of the medium on washing effected by the cyclone is studied in an attempt to determine the cause or causes of the lack of agreement between the various methods of expressing coal-cleaning efficiency. In addition, data obtained by other workers are reviewed to demonstrate the lack of agreement between these various efficiencies. A summary of the data illustrating the influence of the above mentioned variables is presented in Table XIV. These experiments were conducted under the following constant conditions; inlet feed area 0.78 square inches, overflow vortex finder diameter 1.03 inches, inlet feed pressure 13.5 p.s.i.g., pulp ratio six-to-one, feed coal Cadomin 10- to 100-mesh. The data in Table XIV are divided into four sections; the experiments in each section were conducted with a constant specific gravity of

TABLE XIV

Data for Cyclone Separations Showing Influence of Underflow to Overflow Area Ratio and Specific Gravity of Medium

	Specific Gravity of Medium																
	1.30					1.35				1.40				1.45			
Experiment No.	40	32	49	58	54	60	31	59	28	35	30	56	27	39	29	57	26
Underflow Apex Diameter in.	0.58	0.63	0.66	0.73	0.78	0.58	0.63	0.73	0.78	0.58	0.63	0.73	0.78	0.58	0.63	0.73	0.78
Underflow to Overflow Area Ratios	0.31	0.37	0.41	0.50	0.58	0.31	0.37	0.50	0.58	0.31	0.37	0.50	0.58	0.31	0.37	0.50	0.58
Yield of Washed Coal %	81.0	8.20	79.7	54.0	53.6	86.5	85.2	75.4	72.8	88.5	88.0	80.4	78.5	91.2	90.0	85.1	82.2
Ash Content of Washed Coal %	9.5	9.4	9.1	6.2	6.5	10.6	10.7	8.3	7.5	11.5	11.3	9.3	8.5	12.2	11.7	10.4	9.2
Ash Content of Refuse %	51.2	53.0	51.1	31.4	30.8	59.7	60.0	46.1	44.2	62.6	62.1	53.6	49.5	68.3	64.1	59.4	55.0
Specific Gravity of Separation	1.69	1.64	1.61	1.40	1.41	1.76	1.73	1.56	1.53	1.80	1.79	1.62	1.56	1.98	1.84	1.70	1.63
Probable Error	0.070	0.074	0.073	0.066	0.064	0.074	0.076	0.062	0.054	0.077	0.076	0.053	0.043	0.088	0.072	0.058	0.043
Error area Sq.cm.	51.6	53.2	46.0	39.0	41.1	51.2	55.3	42.4	40.2	57.1	59.7	38.1	37.2	62.3	60.1	39.7	39.7
Area Efficiency %	81.2	79.2	82.1	84.8	84.0	80.0	78.4	83.4	84.3	77.7	76.7	85.1	85.5	75.7	76.6	84.5	84.5
Fraser-Yancey Efficiency %	97.4	97.5	97.5	82.8	78.1	98.7	98.6	96.7	96.7	98.2	98.8	98.2	97.2	99.5	99.2	99.3	97.5
Misplaced Material %	5.5	4.9	4.0	13.5	16.1	4.1	4.5	8.6	7.8	2.1	2.1	3.3	6.4	2.1	2.8	3.7	3.2
± 0.10 Specific Gravity %	9.5	10.0	9.8	47.0	47.3	7.2	6.9	18.7	15.5	7.8	6.2	12.0	15.0	3.0	4.9	6.7	8.7
Calculated Ash Content of Feed Coal %	17.4	17.3	17.6	17.8	17.4	17.2	17.9	17.6	17.5	17.0	17.4	18.0	17.3	17.1	17.0	17.7	17.3

suspension and various sizes of underflow opening. These data give the yields and ash contents of the products as well as the specific gravities of separation. They also show the efficiency of cleaning, as measured by the various methods which have been discussed previously.

(1) SPECIFIC GRAVITY OF SEPARATION

There has been a considerable amount of debate as to whether or not the distribution curve (and therefore the Probable Error and Error Area) is independent of the specific gravity of separation. Yancey and Geer (47), maintain that the distribution curve is virtually independent of the specific gravity of separation. Vissac (46) Tromp (30) and the French investigators at Cerchar (3), on the other hand, take the stand that the Probable Error increases with higher specific gravities of separation. In the following subsection the views and arguments of both sides are presented.

(i) Previous Work

As mentioned above the French Cerchar investigators state that the slope of the distribution curve is dependent on the specific gravity of separation. They have proposed a function called the "Magnitude of Imperfection" I, by which the sharpness of separation achieved by coal-washing equipment operating at different specific gravities of separation can be compared.

$$I = \frac{E}{d_p - 1}$$

where I = Magnitude of Imperfection
E = Probable Error
d_p = Specific Gravity of separation

However, no data have been presented by the Cerchar investigators to demonstrate the relationship between specific gravity of separation

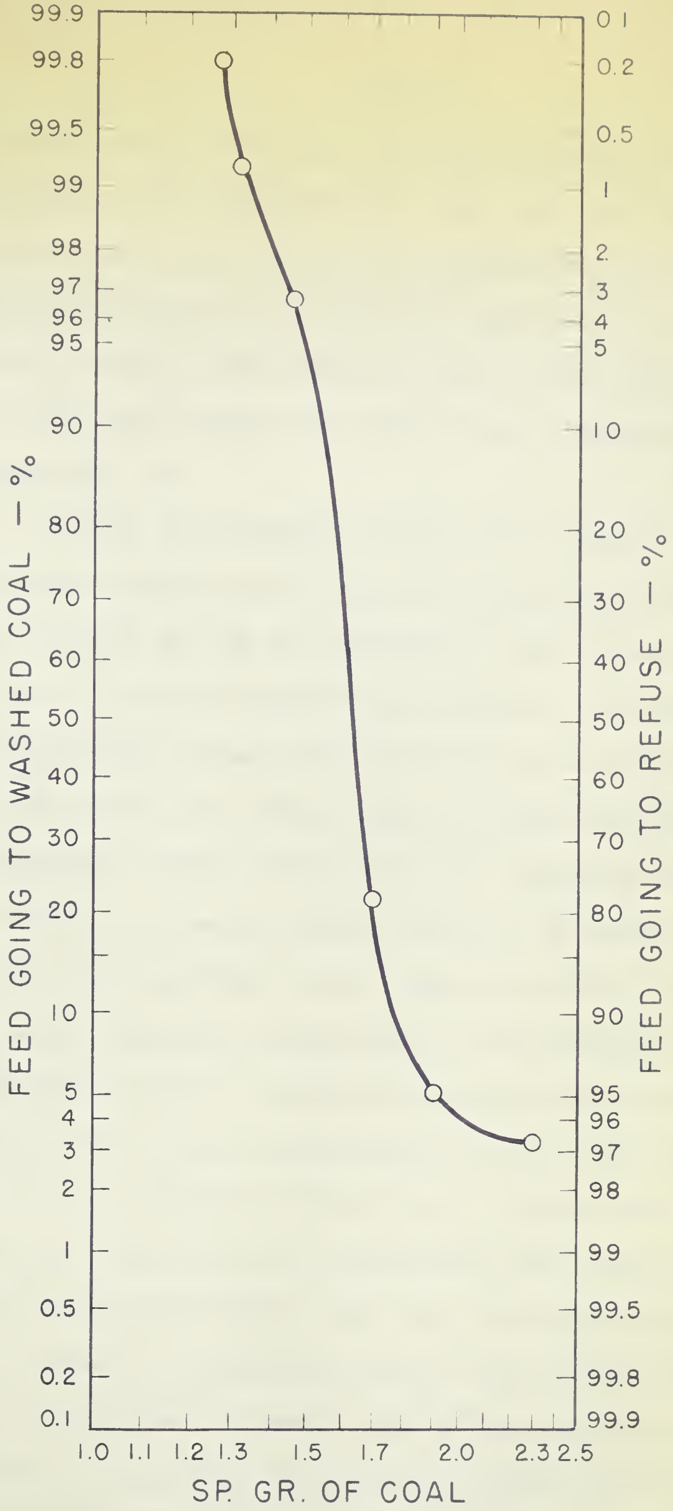

Fig. 13 Transformed distribution curve for cyclone separation of Experiment No, 26 using probability scale for ordinate and logarithmic scale for abscissa.

and Probable Error, nor has any reason been given for dividing the Probable Error by the quantity d_p-1, other than that "mathematically I (the Magnitude of Imperfection) is approximately the reciprocal of the anamorphosed curve for a separation conforming to the logarithmic-normal law, whereas E (the Probable Error) is the reciprocal of the slope of the anamorphosed curve representing a separation following the normal law" (3).

Cerchar investigators (3) have stated that the distribution curves, which normally have a reversed S-shape, can be transformed into straight lines by the use of a probability scale on the ordinate. Three types of scale are used for the abscissa. It is asserted that most coal-cleaning devices give separations whose distribution curves can be transformed into straight lines by using a logarithmic scale for the specific gravity of the coal on the abscissa. Where this is not successful the specific gravity minus one is plotted on the abscissa, still using the logarithmic scale. Separations of this type are said to follow the "logarithmic-normal law". The distribution curves of other separations can be transformed into straight lines by using an arithmetic scale for the specific gravity of the coal on the abscissa. These are said to follow the "normal law". Belugou and de Chawlowski (4) of Cerchar obtained cyclone separations whose distribution curves followed the so-called "normal law", i.e. the curves could be transformed by using the probability scale for the ordinate and an arithmetic scale for the abscissa. However, none of the separations performed by the cyclone in the present investigation followed either the so-called "normal" or "logarithmic-normal laws", since the transformed curves

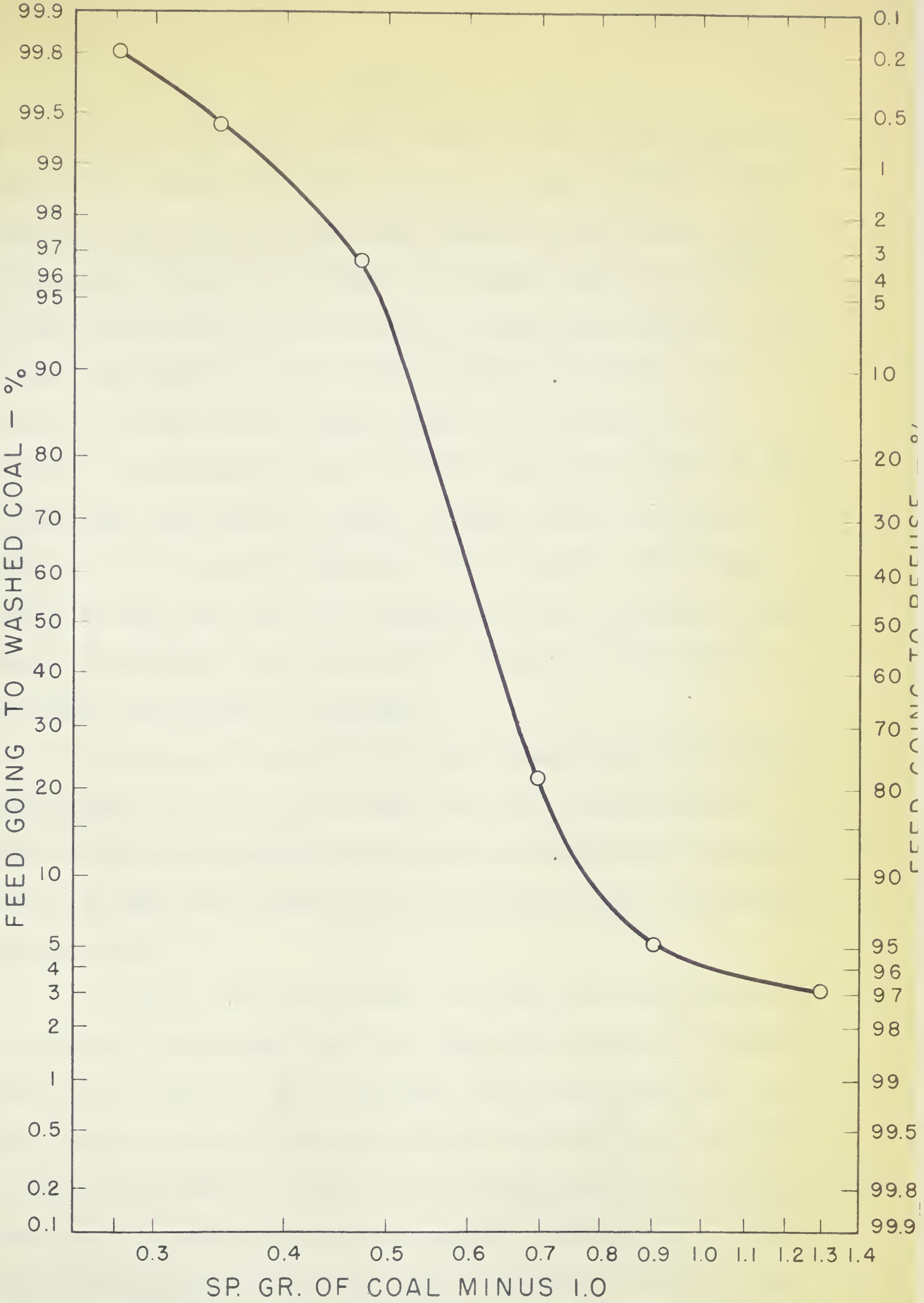

Fig. 14 Transformed distribution curve for cyclone separation of Experiment No. 26 using same scales as Fig. 13 but with specific gravity of coal minus 1.0 rather than specific gravity of coal plotted as abscissa.

all had a reversed S-shape similar to that of the original distribution curve. This coincided with the experience of Yancey and Geer (47) who report that they "have plotted a large number of distribution curves on the scales advocated by Cerchar, with varying degrees of success. The data always show some curvature, and in many cases plotting as a straight line involves a significant sacrifice in accuracy. The reports of Cerchar contain a great number of distribution curves plotted on a probability scale, but in most cases the accuracy of the straight-line representation cannot be judged because the plotted points are not shown and no numerical data are given. Even though Cerchar advocates the use of the straight-line type of plot, it admits that no distribution data form a perfect straight line and that in many cases the deviation is serious."

Belugou and Vitaux (5) of Cerchar showed transformed distribution curves for a rheolaveur washer which had a shape similar to those obtained in the present investigation, although the distribution curves for other coal-cleaning devices demonstrated good straight-line transformation.

In Fig. 13 the distribution curve for the cyclone separation accomplished in Experiment No. 26 has been plotted using the probability scale for the ordinate and a logarithmic scale on the abscissa. In Fig. 14 the same scales have been employed for ordinate and abscissa as in Fig. 13; however, in Fig. 14 the specific gravity of the coal minus one is plotted rather than the specific gravity. Fig. 15 shows the transformed distribution curve when an arithmetic scale was used for the abscissa. The cyclone separations in the present investigation

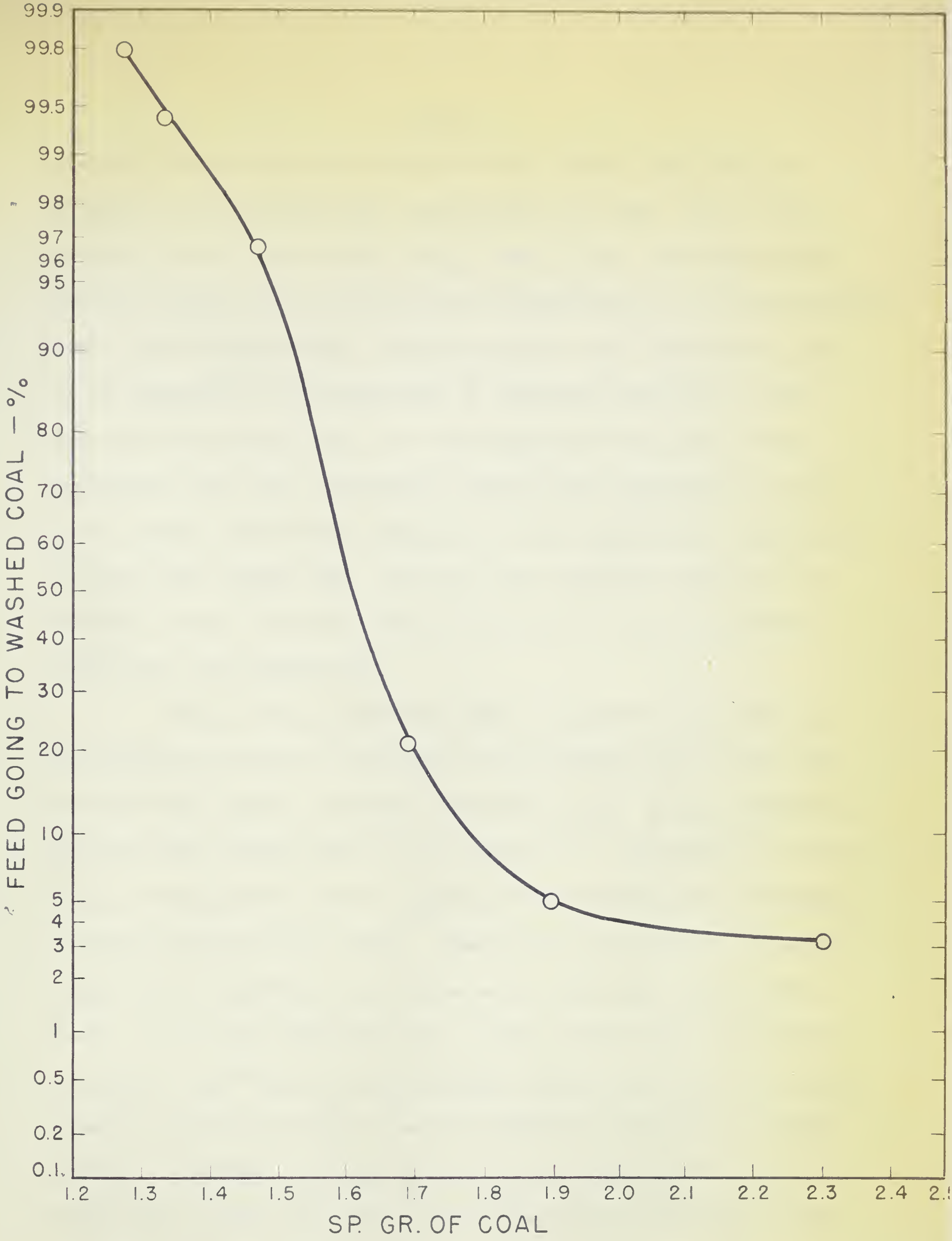

Fig. 15 Transformed distribution curve for cyclone separation of Experiment No. 26 using probability scale for ordinate and arithmetic scale for abscissa.

yielded distribution curves which all had a similar shape when an attempt at such straight-line transformation was made. None of the foregoing curves are straight lines. There is thus some doubt regarding the validity of the method for the transformation of the distribution curves into straight lines. Cerchar engineers have justified the use of the "Magnitude of Imperfection", I, mentioned previously, on the premise that mathematically I is the reciprocal of the slope of the transformed curve for a separation following the "logarithmic-normal law", whereas, the Probable Error, E, is the reciprocal of a separation following the "normal law". In view of the foregoing evidence, it is doubtful whether the reciprocals of the slopes of these transformed curves have any significance.

Vissac has presented data (46) to illustrate the effect of the specific gravity of separation on the probable error but the data were not free from the influence of particle size. It was demonstrated that with the various sizes of coal treated in a jig handling an unsized feed, the separations made at higher specific gravities were characterized by greater probable errors. However, the separations made at the higher specific gravities were those made on the finer sizes of the feed. As has been indicated in the section illustrating the influence of particle size* on cyclone performance, separations made on the finer sizes are achieved at higher specific gravities with greater probable errors. Therefore, as Yancey and Geer have pointed out (47), it is likely that in this case, the particle size had more influence on the probable error than did the specific gravity of separation.

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*See page 88.

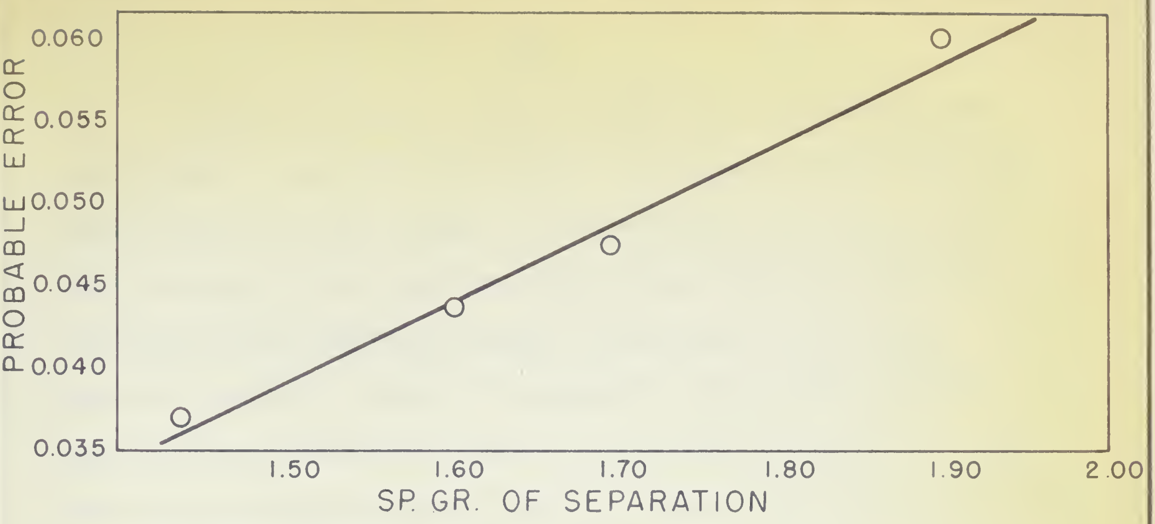

Fig.16a Probable error vs. specific gravity of separation–Burton's data (11)

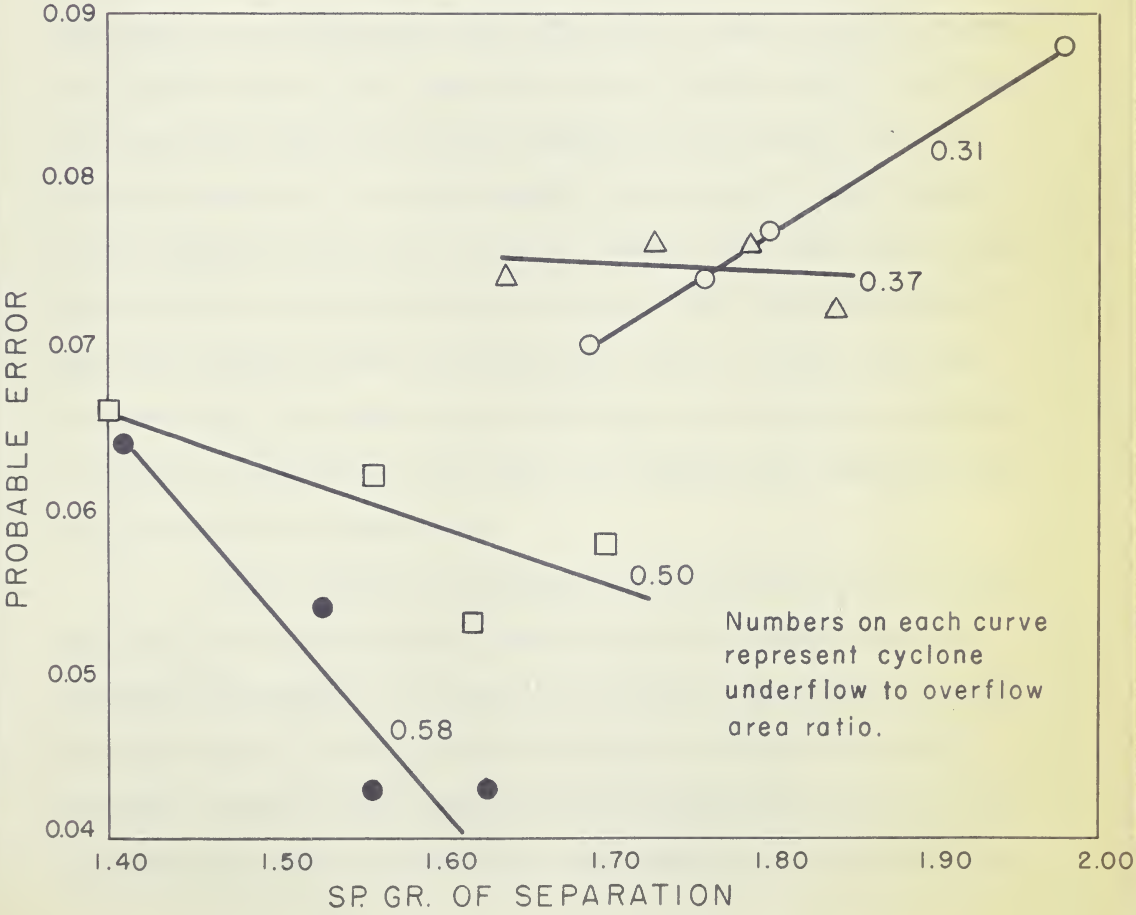

Fig.16b Data for cyclone experiments plotted in same way as Burton's data in Fig. 16a

Burton (11) made a series of tests with the cyclone washer on fine coal in which all the variables were held constant except the specific gravity of the medium. It was concluded that the Probable Error increased as the specific gravity of separation was increased and that this was due to the greater "viscosities" at the higher specific gravities. A plot of the probable errors versus specific gravity of separation from Burton's data is shown in Figure 16a. While this seems conclusive evidence that the probable errors do increase with higher specific gravities of separation, the data obtained in the present investigation (Table XIV) when plotted in a similar manner indicated that this is not necessarily true (Fig. 16b). Each of the four curves was obtained with a fixed underflow-opening diameter and all variables held constant except the specific gravity of the medium. When the ratio of underflow to overflow-opening area was 0.31 a curve similar to that shown by Burton was obtained. However, the other three ratios of underflow to overflow-opening area gave curves which demonstrated that the probable errors decreased at the higher specific gravities of separation. It would appear, therefore, that Burton has presented insufficient evidence to prove that the probable error increases with specific gravity of separation.

Yancey and Geer, in disagreement with Vissac, Burton, Tromp and the Cerchar investigators, maintain that the Probable Error is virtually independent of the specific gravity of separation, at least for the range of specific gravities at which washeries are usually operated. They cite data obtained from an experiment made with a wet concentrating table to substantiate this stand (47). Tromp (30) con-

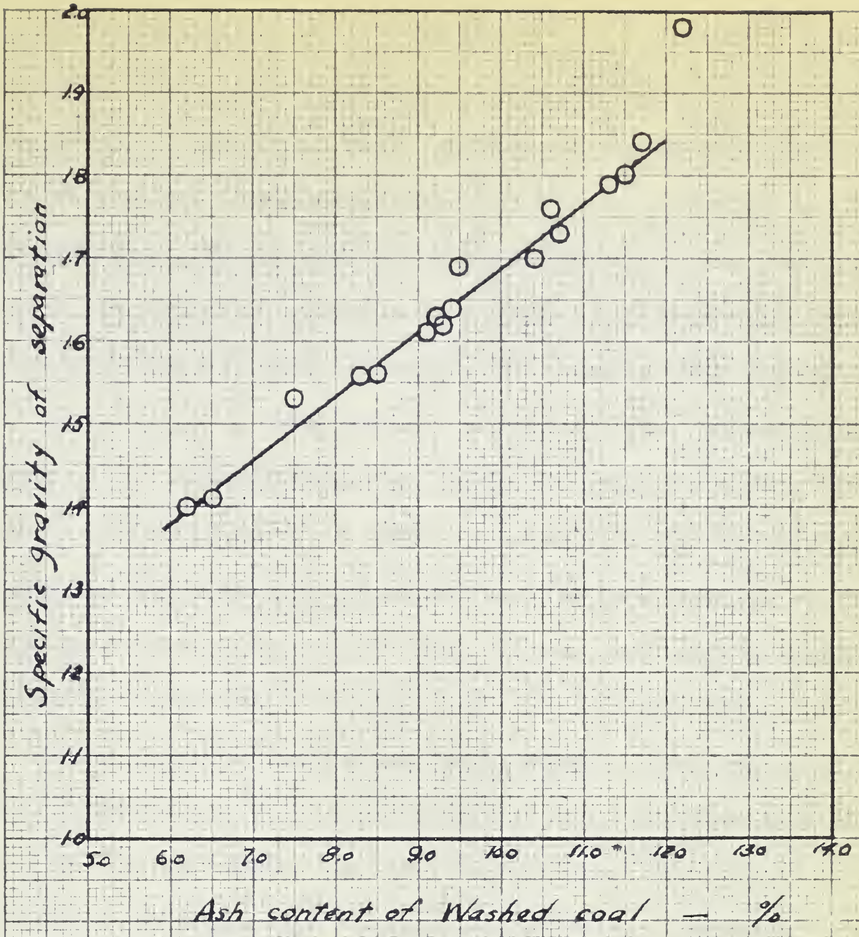

Fig.17. Plot illustrating approximate straight-line relationship between the specific gravity of separation and the ash content of the washed coal.

tends that these separations are not comparable because the data for the individual zones were added together to provide separations at various specific gravities and thus the time of separation was different for each case. Tromp maintains that, in this case, the separations at the lower specific gravities were obtained by shortening the path along which the particles travelled, and therefore the time available for the particles to sort themselves out was less. This objection seems to be a reaonable one, but should not apply to washing accomplished with the cyclone, in which the separation time is very short. Yancey and Geer have also presented data for three cyclone separations which gave identical probable errors. These were made at specific gravities of separation of 1.56, 1.63, and 1.75 with error areas of 37, 41 and 43 square centimeters respectively. Tromp (30) pointed out that if these error areas were divided by the respective specific gravities of separation, the resulting quotients were almost constant, with values of 24.4, 25.1 and 24.6 respectively. Therefore, Tromp maintained that this was evidence that the sharpness of separation decreases as the specific gravity of separation increases.

(ii) Present Investigation

In the preceding subsection the views of various coal-preparation authorities have been presented concerning the influence of the specific gravity of separation on the Probable Error and Error Area; in this and the following subsections the cyclone data shown in Table XIV are analysed in an attempt to find the reasons for the divergence of opinion on this subject. The cyclone data are also analysed in an endeavour to find the cause or causes of the disagreement

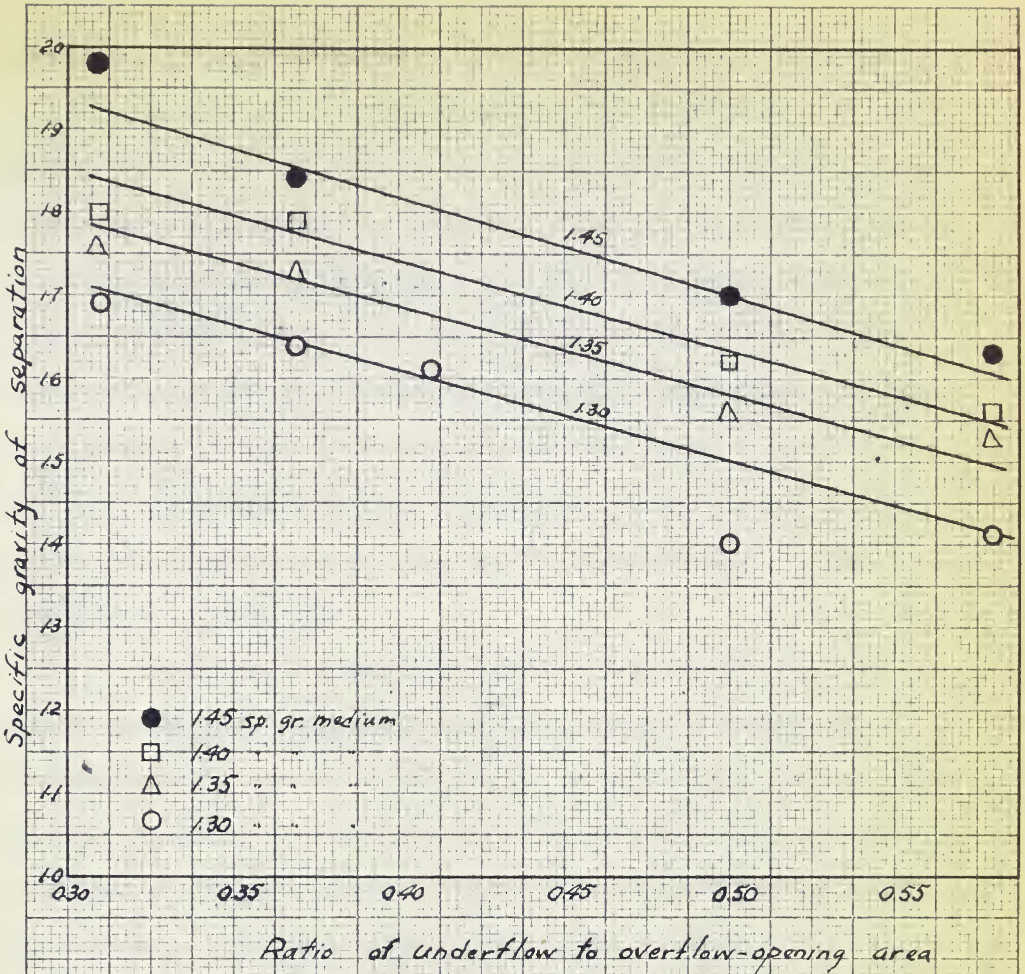

Fig.18 Cyclone data illustrating change in specific gravity of separation when ratio of underflow to overflow - opening area is varied.

between the various efficiencies by which coal-cleaning is measured.

In Fig. 17 the specific gravities of separation have been plotted against the ash contents of the washed coal from the cyclone separation data presented in Table XIV. This plot illustrates that for this feed coal and under these operating conditions, there is a general straight-line relationship between the ash content of the washed-coal product and the specific gravity of separation. It is thus possible to predict the approximate ash content of the washed-coal from the specific gravity of separation providing that all of the operating conditions are the same as those outlined for the experiments of Table XIV.

In Fig. 18 the specific gravity of separation has been plotted against the ratios of underflow to overflow-opening area* with the specific gravity of the medium as parameters. In Fig. 19 the specific gravities of separation have been plotted versus the specific gravities of the suspensions with the ratios of underflow to overflow-opening area as parameters. These two figures represent a cross-plot of the data, showing the manner in which the specific gravity of separation varies with changes in the two variables. The curves for the 1.30, 1.35, 1.40 and 1.45 specific gravity suspension in Fig. 18 are approximately parallel. Similarly in Fig. 19 the curves for the four constant cyclone dimensions with ratios of underflow to overflow opening area of 0.31, 0.37, 0.50 and 0.58 are approximately parallel.

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*The ratios of the underflow-opening area to the overflow opening area are used throughout this thesis although the overflow opening was held constant and the underflow-opening only was varied. The area ratios are used because they are thought to be a more fundamental cyclone dimension than the sizes of the underflow opening alone.

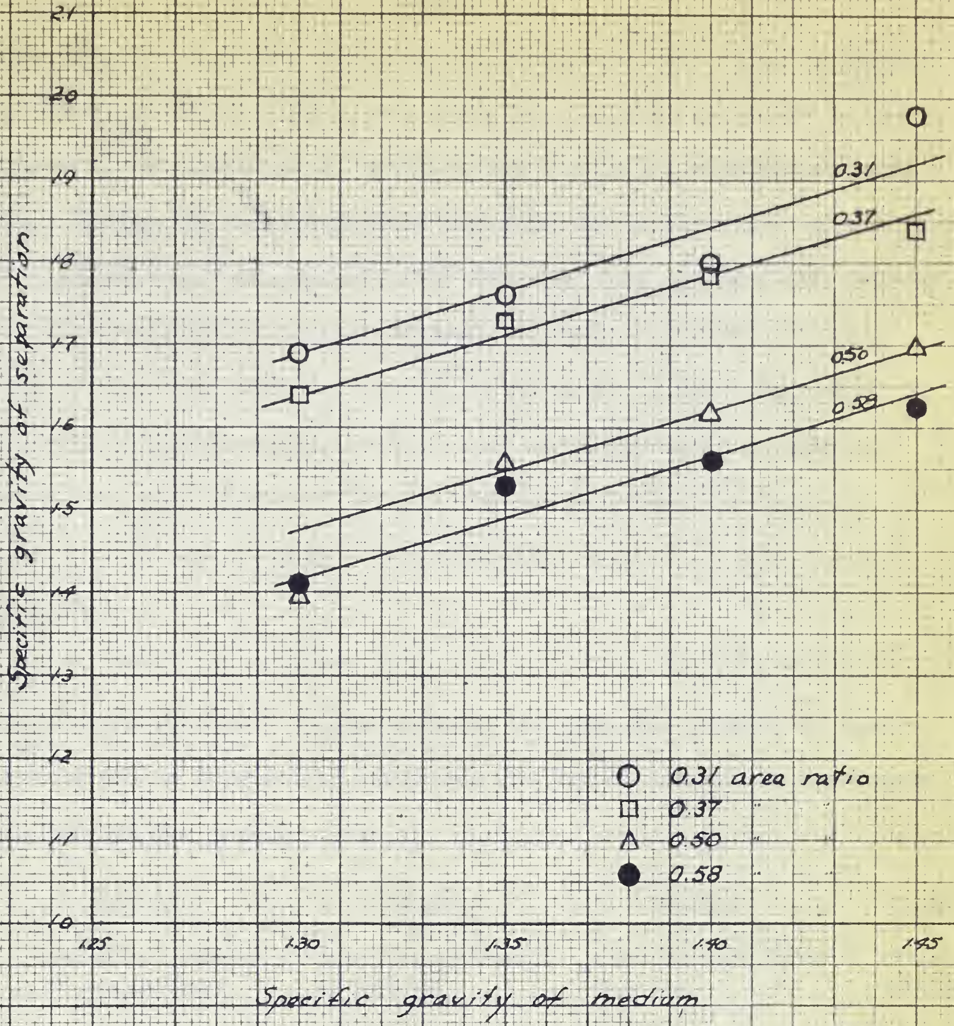

Fig. 19 Variation in specific gravity of separation for constant cyclone dimensions as specific gravity of medium is varied. Numbers on curves refer to cyclone underflow to overflow-opening area ratios.

These diagrams show that the specific gravity of separation is approximately a linear function of the type $y = m x + b$ where "b" is the intercept, "m" the slope of the line and "x" is the independent variable. In Fig. 18 the independent variable "x" is the ratio of underflow to overflow area. The slope "m" is approximately constant for all the specific gravities of medium employed, while the constant "b" is different for each medium since it is the value of the intercept. In Fig. 19 the independent variable "x" is the specific gravity of the medium. The slope "m" in this case is approximately constant for the ratios of underflow to overflow-opening area of 0.31, 0.37, 0.50, and 0.58.

These two diagrams (Figs. 18 and 19) demonstrate that for coal washing performed by the cyclone, the specific gravity of separation is not an independent variable; it may be likened to the volume in a very simple analogy, viz:

Volume:	length,	width,	height.
Specific gravity of separation	specific gravity of medium	size of underflow opening	other variable

In this example, the volume depends upon the length, width, and height. When the height is held constant, the volume depends upon the length and width. If the length is fixed the volume depends upon the width and if the width is fixed the volume depends upon the length. By analogy, the specific gravity of separation depends upon the specific gravity of the medium, size of the underflow opening and all other variables. The height is analogous to the numerous other variables which are held constant. Under these conditions the specific gravity

of separation depends upon the specific gravity of medium and the size of the cyclone underflow opening; when the suspension specific gravity is fixed the specific gravity of separation depends upon the size of the cyclone underflow-opening and when the latter is fixed the specific gravity of separation depends upon the specific gravity of the medium. These results may help to explain the divergence of opinion as to whether or not the distribution curve is independent of the specific gravity of separation. It would seem from the arguments advanced by the workers mentioned in the previous subsection that they have assumed that the specific gravity of separation is an independent variable; Figs. 18 and 19 demonstrate that this is not so. This aspect will be discussed in more detail in the following sections.

It will be noted that one point in Figs. 18 and 19 has been disregarded; this is for the separation performed with the 1.30 specific gravity medium and the 0.50 ratio of underflow to overflow-opening area. The reason for doing so becomes apparent on examination of the curves in Fig. 19. The curves for the 0.37, 0.50 and 0.58 ratios of underflow to overflow-opening area are parallel if the specific gravity of separation for the above-mentioned separation is not included. Similarly in Fig. 18, the curves for all the specific gravities of suspension from 1.30 to 1.45 are parallel if this point is again disregarded. A well-established trend was demonstrated by the other specific gravities of separation; therefore, it was believed that under the operating conditions cited for this experiment the specific gravity

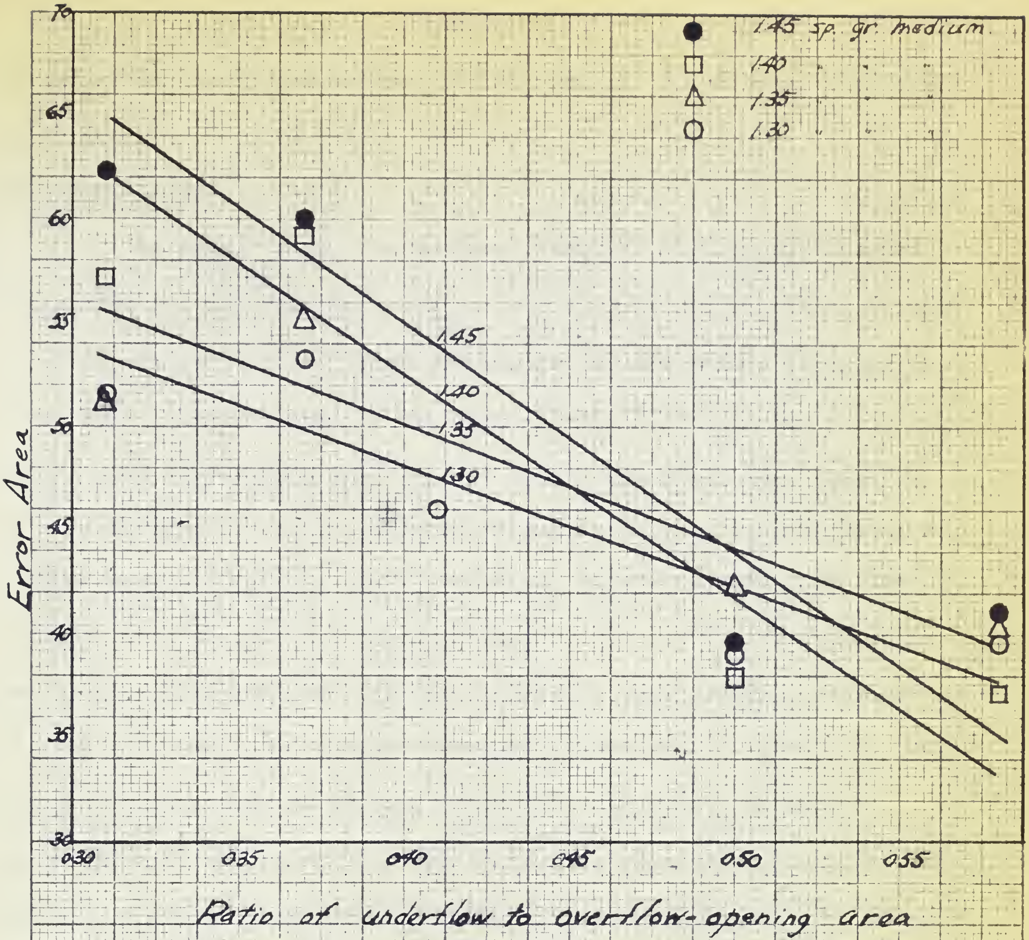

Fig. 20 Cyclone data illustrating error areas for constant suspension specific gravities as ratio of underflow to overflow-opening area is varied.

of separation should have been greater than the value of 1.40 actually obtained.

(2) ERROR AREA

In Figs. 20 and 21 the Error Area has been plotted versus the ratios of underflow to overflow-opening area and specific gravity of medium respectively. These cross-plots of the data correspond to Figs. 18 and 19 in which the specific gravity of separation was plotted against the same variables. Fig. 18 shows that there is a uniform rate of change in specific gravity of separation for each suspension as the underflow opening size is changed, since the curves are approximately parallel straight lines. However, Fig. 20 demonstrates that the change in Error Area does not follow the same pattern. The curves for the 1.30 and 1.35 specific gravity suspensions are parallel, indicating a uniform rate of change in the Error Area with these two suspensions as the underflow opening size is changed. The curves for the 1.40 and 1.45 specific gravity media are parallel but have steeper slopes than those for the 1.30 and 1.35 suspensions. Therefore, considering Figs. 18 and 20 it is evident that with the 1.30 and 1.35 suspension specific gravities, the Error Area increases from 38 to 53 and from 40 to 55 respectively when increasing specific gravities of separation are obtained by changing the ratio of cyclone underflow to overflow opening area from 0.58 to 0.31. With the 1.40 and 1.45 specific gravity media, the Error Area shows a greater increase from 34 to 62 and from 35 to 65 respectively, at higher specific gravities of separation when the latter are again achieved by decreasing the size of the cyclone underflow opening.

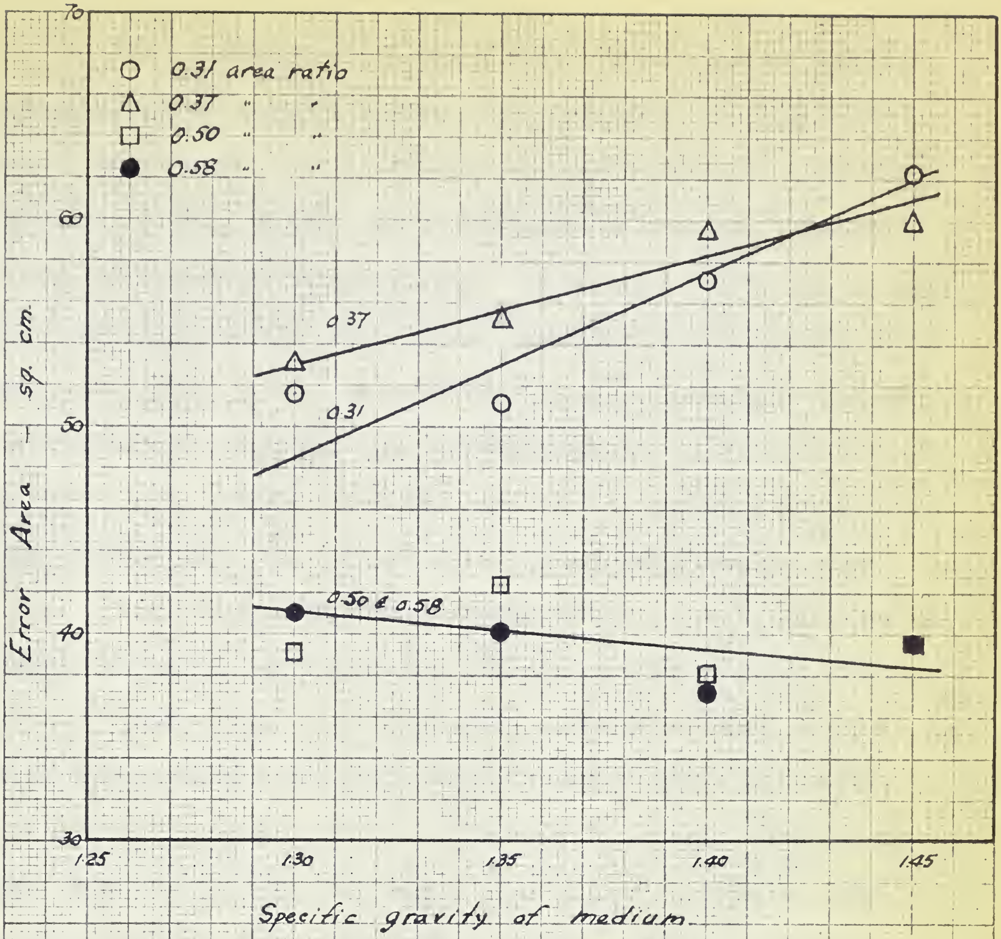

Fig. 21 Error Areas for constant cyclone dimensions as specific gravity of medium is varied. Numbers on curves refer to cyclone underflow to overflow – opening area ratios.

It is problematical whether the curves in Fig. 20 should be represented by S-shaped curves or by straight lines. The Error Area versus specific gravity of medium curves in Fig. 21 together with the curves in Fig. 20 represent a cross-plot of the data. The curves in Fig. 21 seem to be best represented by straight lines. The straight-line representation also seems to best suit the plot of Probable Error versus area ratio in Fig. 22 which corresponds to a similar plot for the Error Area in Fig. 20. The Probable Error is an approximation of the Error Area, and the two should give similar results. Because of these circumstances the straight-line representation was chosen.

Fig. 21 demonstrates that each Error Area curve for constant cyclone dimensions has a characteristic slope; this slope is different for each cyclone underflow to overflow-opening area ratio, being a fairly steep positive slope for the 0.31 ratio, less steep for the 0.37 ratio, and negative for the 0.50 and 0.58 ratios. Thus for the small underflow opening (0.31 ratio of underflow to overflow area), the Error Area increases with higher specific gravities of medium; since the specific gravity of separation also increases with greater suspension specific gravities, this means that for these cyclone dimensions the Error Area rises from 49 to 62 (Fig. 20) when the specific gravity of separation is raised from 1.65 to 1.94 (Fig. 18) by changing the specific gravity of the medium from 1.30 to 1.45. Similarly for the 0.37 ratio of underflow to overflow-opening area, the Error Area shows a similar though less pronounced trend, changing from 53 to 61 as the specific gravity of separation is raised from 1.65 to 1.85. It will be noted that the curve is less steep than the preceding one. However, for the 0.50 and 0.58 ratios the curve common

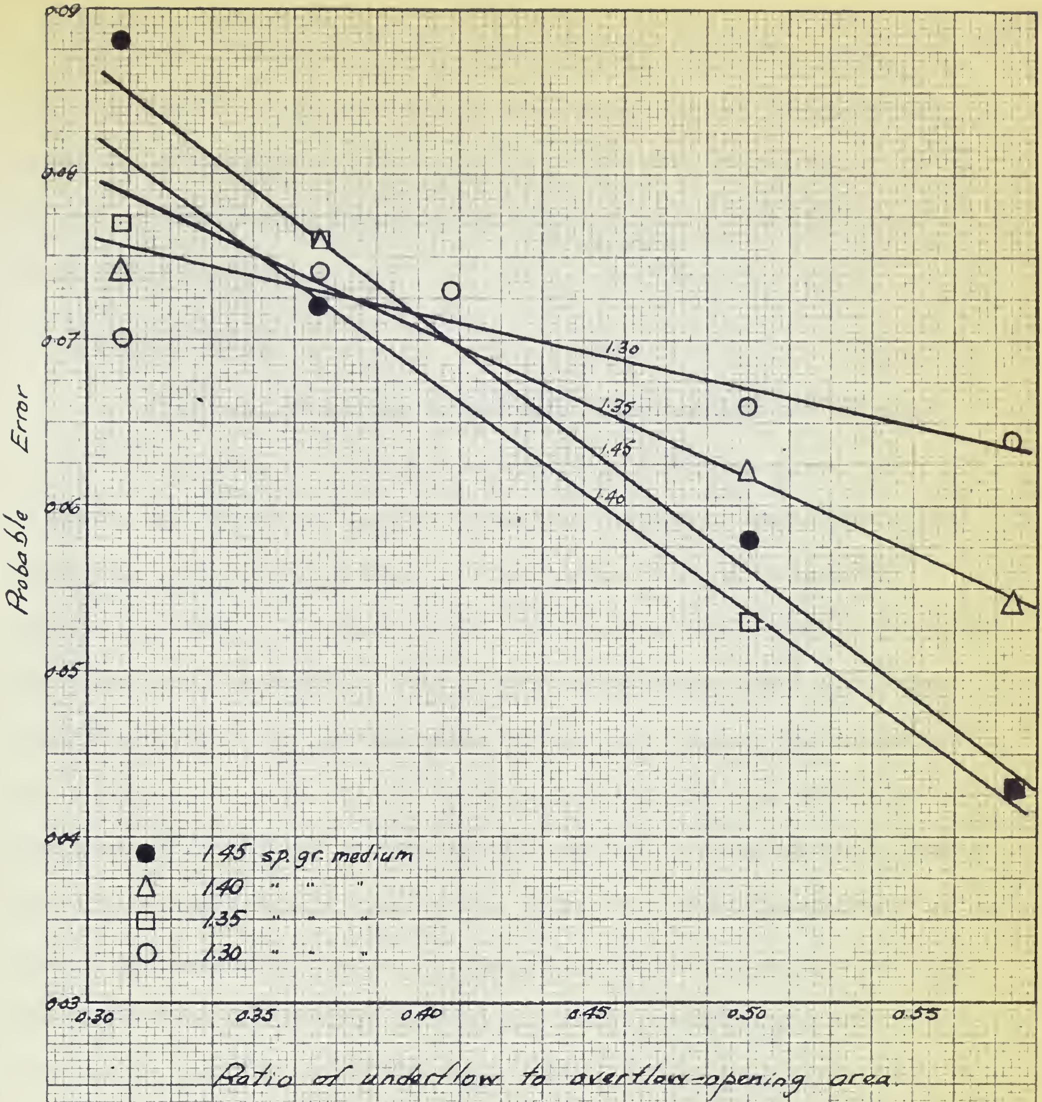

Fig. 22 Curves illustrating variation in Probable Error for constant suspension specific gravities as ratio of underflow to overflow - opening area of cyclone is varied.

to both shows a negative slope, indicating that the Error Areas now decrease from 41 to 38 for both cyclone dimensions as the specific gravities of separation are raised from 1.48 to 1.70 and from 1.42 to 1.64 respectively by varying the specific gravity of the medium from 1.30 to 1.45.

(3) PROBABLE ERROR

In Figs. 22 and 23, the probable errors have been plotted against the ratios of underflow to overflow-opening area and the specific gravity of the medium in the same manner as the error areas were plotted in Figs. 20 and 21. The curves in Figs. 22 and 23 demonstrate that the probable errors follow the same trend as the error areas in Figs. 20 and 21. This is what might be expected since the Probable Error is an approximation of the Error Area. The curves for the Probable Error in Fig. 22 which correspond with the curves for the Error Area in Fig. 20 have greater negative slopes as the specific gravity of the medium is increased. This means that the probable errors increase with increasing specific gravities of separation when the latter are achieved by varying the underflow-opening area and the suspension specific gravity is held constant. The probable errors increase from 0.064 to 0.076 (Fig. 22) as the specific gravity of separation is increased from 1.42 to 1.70 (Fig. 18) for the 1.30 specific gravity medium. Similarly for the 1.35, 1.40 and 1.45 suspensions the probable errors increase from 0.055 to 0.079, 0.042 to 0.081 and 0.044 to 0.085 for specific gravity of separation increases from 1.50 to 1.78, 1.55 to 1.84 and 1.60 to 1.92. When the probable errors are plotted against the specific gravity of medium with the ratios of underflow to

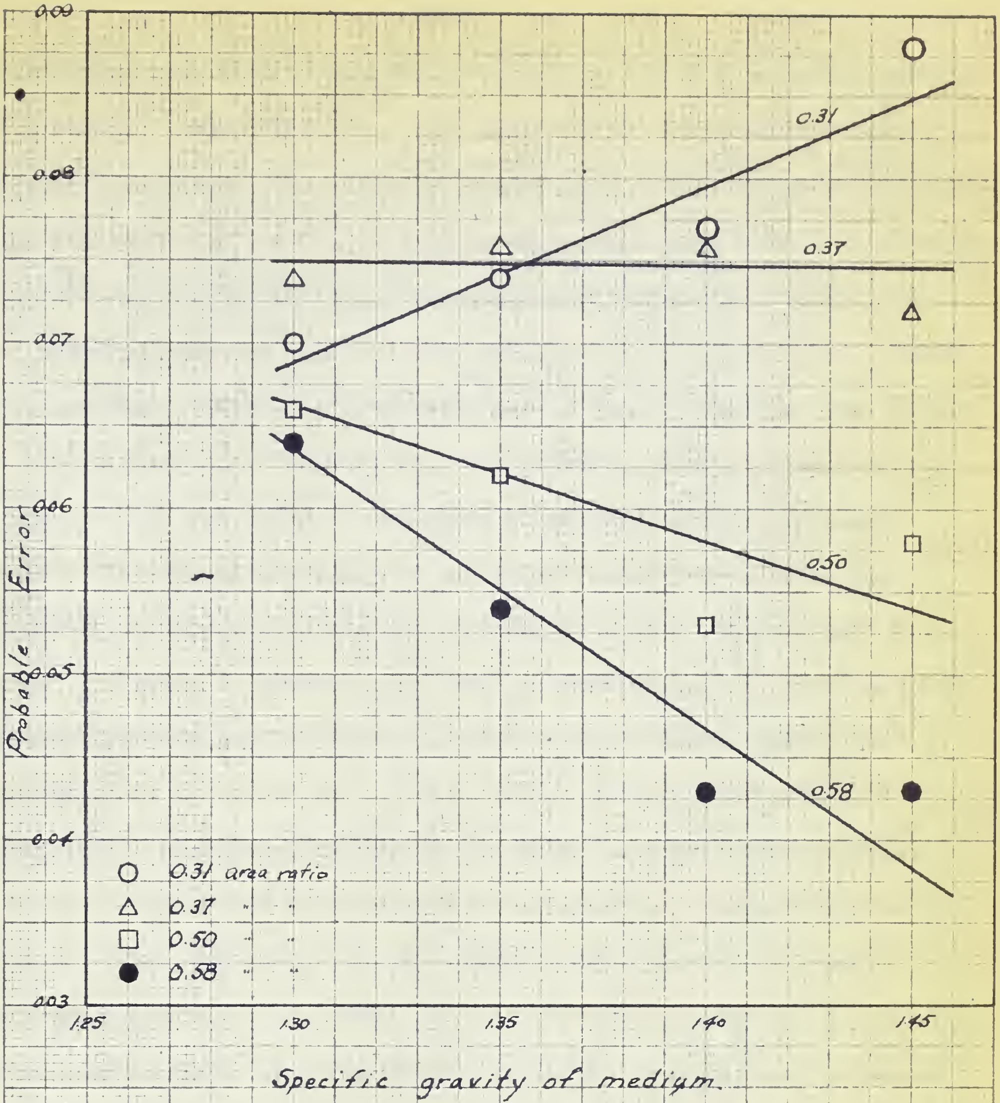

Fig. 23 Curves showing variation in Probable Error for constant ratios of cyclone underflow to overflow - opening area as specific gravity of medium is varied. Numbers on curves refer to ratios of underflow to overflow - opening area of cyclone.

overflow-opening area as parameters as in Fig. 23, the resulting curves have varying slopes; the slopes are greatest for the smallest underflow to overflow-opening area ratio and become less as this ratio is increased. Thus the slope for the 0.31 underflow to overflow area ratio is positive, that for the 0.37 ratio is approximately zero (horizontal) whilst that for the 0.50 ratio is negative and the slope for the 0.58 ratio is still more negative. Thus the probable errors in Fig. 23 show the same trends as do the error areas in Fig. 21. The probable errors increase from 0.069 to 0.085 for the 0.31 underflow to overflow cyclone dimension ratio as the specific gravity of medium is varied from 1.30 to 1.45, producing an increase in specific gravity of separation from 1.65 to 1.94. For the 0.37 underflow to overflow area ratio, the probable error remains approximately constant at 0.075 as the specific gravity of separation is increased from 1.65 to 1.85. With the 0.50 ratio of underflow to overflow-opening area the probable errors decrease from 0.066 to 0.054 as the specific gravity of separation is increased from 1.48 to 1.70. Similarly when the cyclone dimensions are changed so that the underflow to overflow ratio is 0.58 the probable errors decrease from 0.064 to 0.038 as the specific gravity of separation is increased from 1.42 to 1.64.

Although the general trend shown by the Error Area and Probable Error is similar, there is some discrepancy between the results obtained for these two measures of the sharpness of separation. This is undoubtedly due to the fact that the Probable Error takes into account only that part of the distribution curve between 25 and 75% of the ordinate,

whereas the Error Area takes the whole curve into account. In other words, the Probable Error shows the sharpness of separation for the material of intermediate specific gravity, whilst the Error Area shows the sharpness of separation for the complete range of specific gravities.

In a previous subsection, data cited by Yancey and Geer* for three cyclone separations showed identical probable errors while the error areas were 37, 41 and 43 for specific gravities of separation of 1.56, 1.63 and 1.75 respectively. Tromp maintained that this was evidence that the sharpness of separation as shown by the Error Area deteriorated as the specific gravity of separation increased. An examination of the cyclone data in Figs. 21 and 23 may throw some further light on the argument between Tromp and Yancey and Geer concerning the variation in the distribution curve with specific gravity of separation. For the underflow to overflow area ratio of 0.37, as the specific gravity of medium is varied from 1.30 to 1.45, giving a rise in specific gravity of separation from 1.65 to 1.85, Fig. 23 shows that the probable error is approximately constant at 0.075. On the other hand, the error area increases from 53 to 60 under the same conditions (Fig. 21). Thus, in this case, the Probable Error remains constant whilst the Error Area rises with increasing specific gravities of separation. These trends are the same as those shown by the data of Yancey and Geer, but this does not necessarily prove that the Probable Error remains constant or that the Error Area increases with higher specific gravities of separation. These data illustrate that three separations do not supply sufficient evidence on which to base such

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*See page 99.

broad general conclusions, since it has already been shown (Figs. 21 and 23) that the Error Area and Probable Error may either increase or decrease with greater specific gravities of separation. All parties in the argument seem to have disregarded the fact that the specific gravity of separation is not an independent variable but is a dependent variable; for the cyclone washer it depends upon the independent variables of size of underflow opening and specific gravity of the medium providing that all the other variables are fixed.

It will be noted that suspensions with a specific gravity of 1.30 were used to perform washing at specific gravities of separation between 1.61 and 1.69. The only mention in the literature of such low specific gravity suspensions being employed with the cyclone washer to accomplish specific gravities of separation of this order is in the work of Belugou and de Chawlowski (4). For such separations these Cerchar workers obtained probable errors ranging from 0.07 to 0.09, which they considered to be much too great for satisfactory cleaning. They therefore recommended the use of larger ratios of underflow to overflow-opening area and suspensions of higher specific gravity. Figs. 21 and 23, showing the error areas and probable errors resulting from the separations accomplished in the present investigation, demonstrate that much sharper separations are obtained with the larger underflow openings. However, a consideration of the data for two separations presented in Table XV serves to illustrate that satisfactory cleaning is achieved when the probable error is greater than 0.07. The data for Experiment Nos. 26 and 32 are presented in Table XV. Experiment No. 26 was performed with a suspension of 1.45 specific gravity and an

TABLE XV

Comparison of Data for Experiments Nos. 26 and 32

Experiment No.	26	32
Specific Gravity of Medium	1.45	1.30
Yield of Washed Coal %	82.2	82.0
Ash Content of Washed Coal %	9.2	9.4
Ash Content of Refuse %	55.0	53.0
Specific Gravity of Separation	1.63	1.64
Fraser-Yancey Efficiency %	97.5	97.5
Calculated Ash Content of Feed %	17.3	17.3
Probable Error	0.043	0.074
Error Area. sq. cm.	39.7	53.2
Misplaced Material %	3.2	5.0
± 0.10 Specific Gravity %	8.7	10.0

underflow to overflow-opening area ratio of 0.58 whilst a 1.30 specific gravity medium and a ratio of underflow- to overflow-opening area of 0.37 was used for experiment No. 32. These separations were performed at almost the same specific gravity of separation, 1.63 and 1.64 for Experiment Nos. 26 and 32 respectively. The degree of washing difficulty as shown by the ± 0.10 specific gravity value was 8.7% for the feed of Experiment NO. 26 and 10.0% for the feed of Experiment No. 32. Variations of this order do not affect the cleaning results obtained with the cyclone washer so it can be assumed that the effect

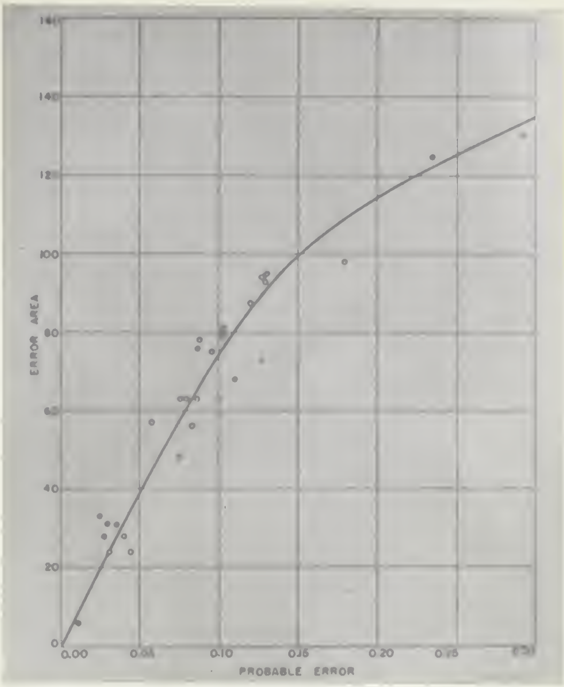

Fig. 24 Yancey and Geer (47) plot of Error Area vs. Probable Error.

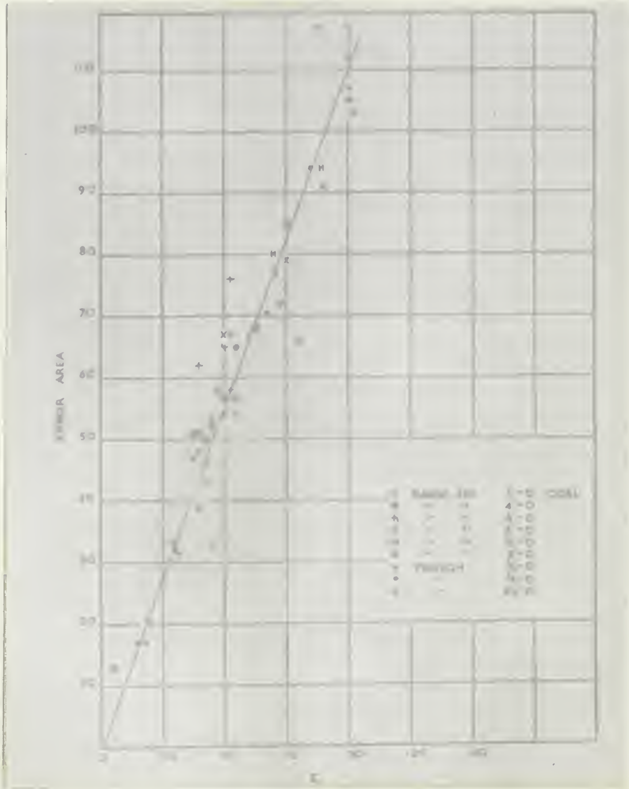

Fig. 25 Grounds and Needham (30) data illustrating approximate straight-line relationship between Error Area and Probable Error.

of the washability of the coal was negligible. The probable error values of 0.043 and 0.074 and the error area values of 39.7 and 53.2 respectively demonstrate that Experiment No. 26 gave much the sharper separation. The yields of 82.2 and 82.0%, washed-coal ash contents of 9.2 and 9.4% and refuse ash contents of 55.0 and 53.0%, respectively, indicate that Experiment No. 26 showed slightly the better performance. However, from the viewpoint of the coal operator, there may not be too much to choose between the two separations, since the yields and ash contents of the products are almost the same. In addition the Fraser-Yancey efficiency for both separations was 97.5%, so that in neither case was there an excessive loss of clean coal. The foregoing data serve to prove that a probable error value of more than 0.07 is not too high for satisfactory coal-cleaning. In view of these results, economics would probably dictate the use of the 1.30 specific gravity medium rather than one of 1.45 specific gravity to perform such a separation. If the 1.30 suspension is used the ratio of cyclone underflow to overflow-opening area is 0.37. This, of course, is much smaller than the ratio of slightly less than one (0.91 for a 350 mm cyclone) advocated by the Cerchar investigators.

Cerchar investigators (3) stated that there is a straight-line relationship between the Probable Error and Error Area and therefore that it is unnecessary to calculate the Error Area. They state that the Error Area = 590 x Probable Error. Yancey and Geer plotted error areas against the corresponding probable errors from coal-washing data which they obtained and found that there was a general relationship between the two, although the upper end of the curve veered away from a straight line (Fig. 24). Grounds and Needham (30) have also

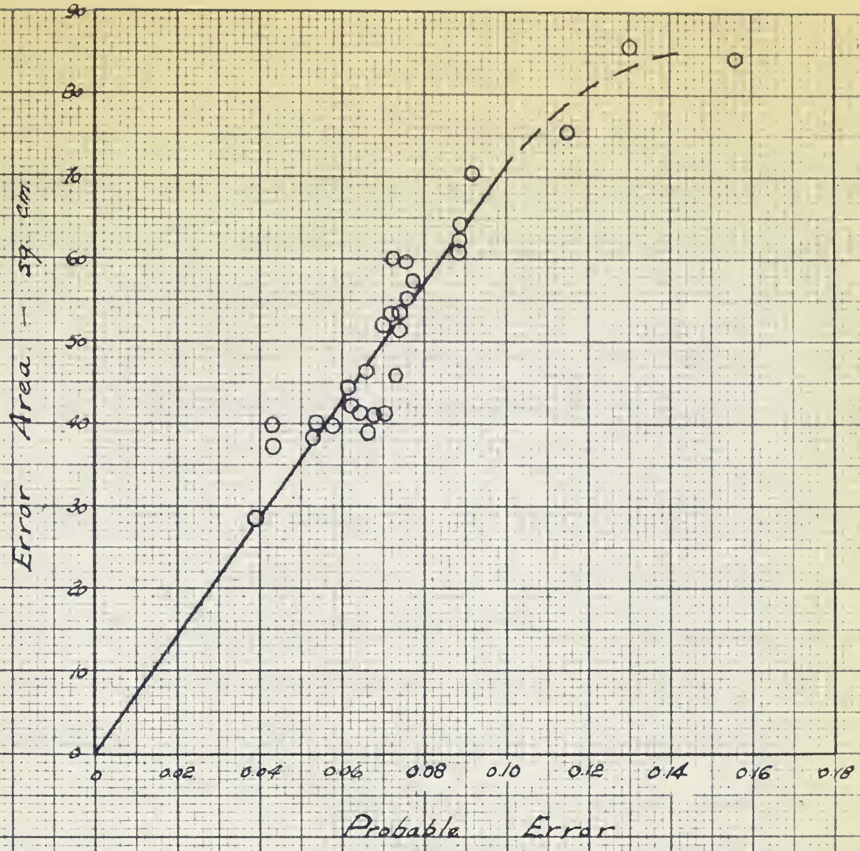

Fig.26 Cyclone data from present investigation illustrating approximate straight – line relationship between Error Area and Probable Error.

shown a plot of error areas versus probable errors (Fig. 25) for a number of separations performed in British coal preparation plants which indicates a general straight-line relationship. An approximate straight-line relationship is also demonstrated by the data obtained from the cyclone separations made for this investigation (Fig. 26). It must be emphasized that this relationship is very approximate and that large errors can result if the Error Area is calculated from the Probable Error on the assumption that one is directly proportional to the other. For example, errors as great as 65% may result from this assumption if applied to the data in Figs, 24, 25 and 26. As stated above, the Cerchar investigators quoted a coefficient of 590 by which to multiply the Probable Error in order to convert it into the Error Area. Values of 730, 550, and 735 respectively, are found for this coefficient from the data of Yancey and Geer, Grounds and Needham, and the present investigation as compared with the value of 590 cited by the French investigators. These results show that the Error Area cannot be calculated with any degree of accuracy by multiplying the Probable Error by some coefficient.

(4) FRASER-YANCEY EFFICIENCY

The Fraser-Yancey efficiencies obtained from the cyclone data in this investigation have been plotted against the ratios of underflow to overflow-opening area with the specific gravities of the medium as parameters in Fig. 27. In Fig. 28 the Fraser-Yancey efficiencies have been plotted versus the specific gravities of the medium with the ratios of underflow to overflow area as parameters. These two figures represent a cross-plot of the data corresponding to Figs. 20 and 21 for the Error Area and Figs. 22 and 23 for the Probable Error.

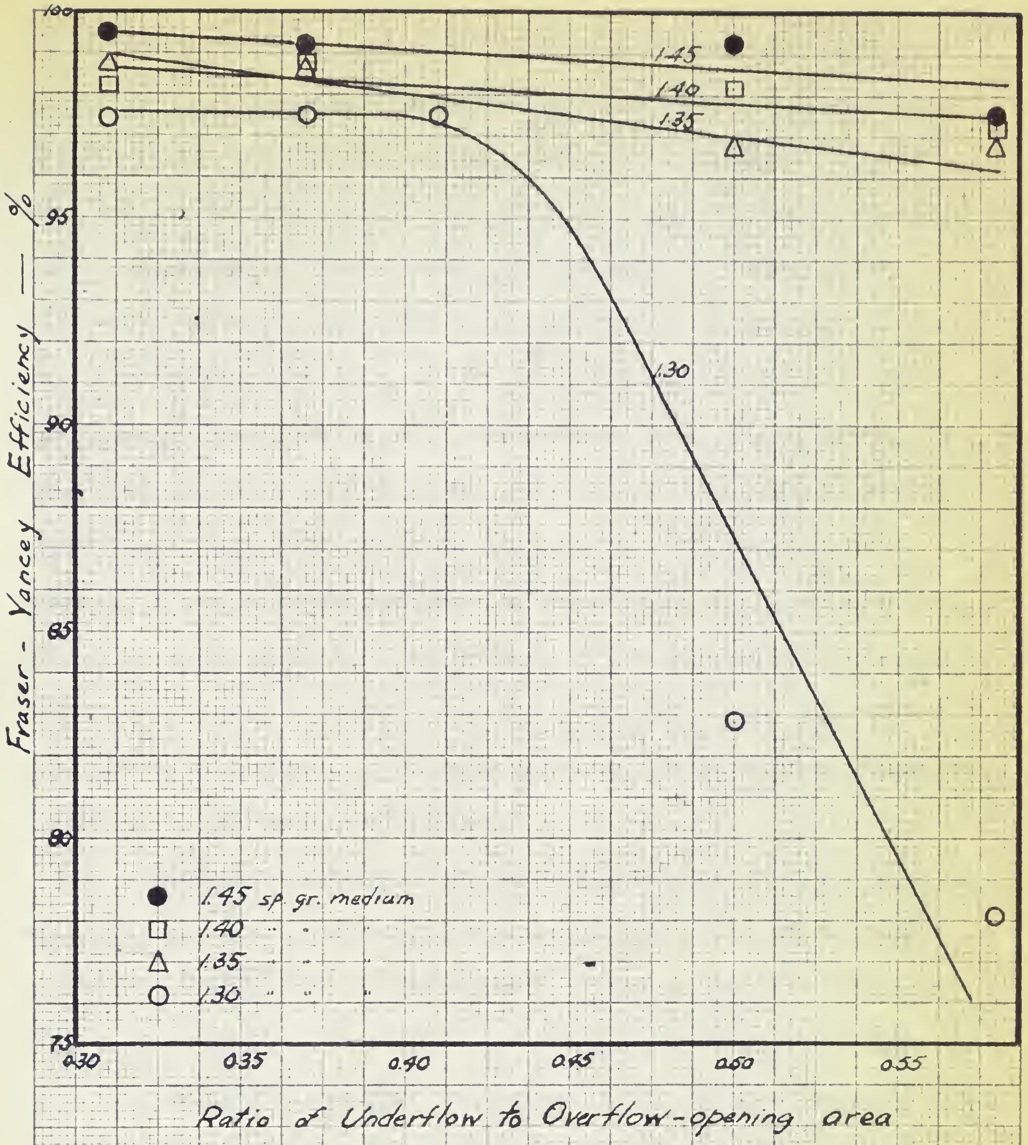

Fig. 27 Curves illustrating variation in Fraser-Yancey Efficiency for cyclone operation with constant specific gravity of medium as ratio of underflow to overflow - opening area is varied.

Fig. 27 demonstrates that the Fraser-Yancey Efficiency exhibits a trend opposite to that displayed by the Error Area* as the specific gravity of separation is increased by decreasing ratios of underflow to overflow-opening area (Fig. 18). For constant suspension specific gravities of 1.45, 1.40, 1.35 and 1.30 the Fraser-Yancey efficiencies increase from 97.5 to 99.4%, 97.1 to 98.6%, 96.0 to 98.7% and 75 to 97.6% respectively as the ratios of underflow to overflow area decrease from 0.58 to 0.31. Under these same circumstances, the Error Area increases from 35 to 64, 33 to 62, 40 to 55 and 39 to 54 respectively (Fig. 20). Since an increase in the latter function denotes a decrease in the sharpness of separation, it is evident that under these conditions the Fraser-Yancey Efficiency exhibits opposite tendencies to those demonstrated by the Error Area, i.e. the Fraser-Yancey shows an increase in efficiency whilst the Error Area indicates a decrease in separation efficiency.

In Fig. 28, the Fraser-Yancey efficiencies have been plotted versus the specific gravities of medium with the ratios of underflow to overflow-opening area as parameters. These correspond to similar plots of the specific gravity of separation, Error Area, and Probable Error in Figs. 19, 21 and 23. The curves in Fig. 28 are identical for the two smaller underflow to overflow area ratios of 0.31 and 0.37, showing a slight increase in Fraser-Yancey Efficiency from 97.5 to 99.0% as the specific gravity of the medium is varied from 1.30 to 1.45. It has been noted previously that under these same conditions the specific gravity of separation rises from 1.65 to 1.94 and from

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*The Error Area is taken as representing the sharpness of separation since the Probable Error is considered to be an approximation of the Error Area.

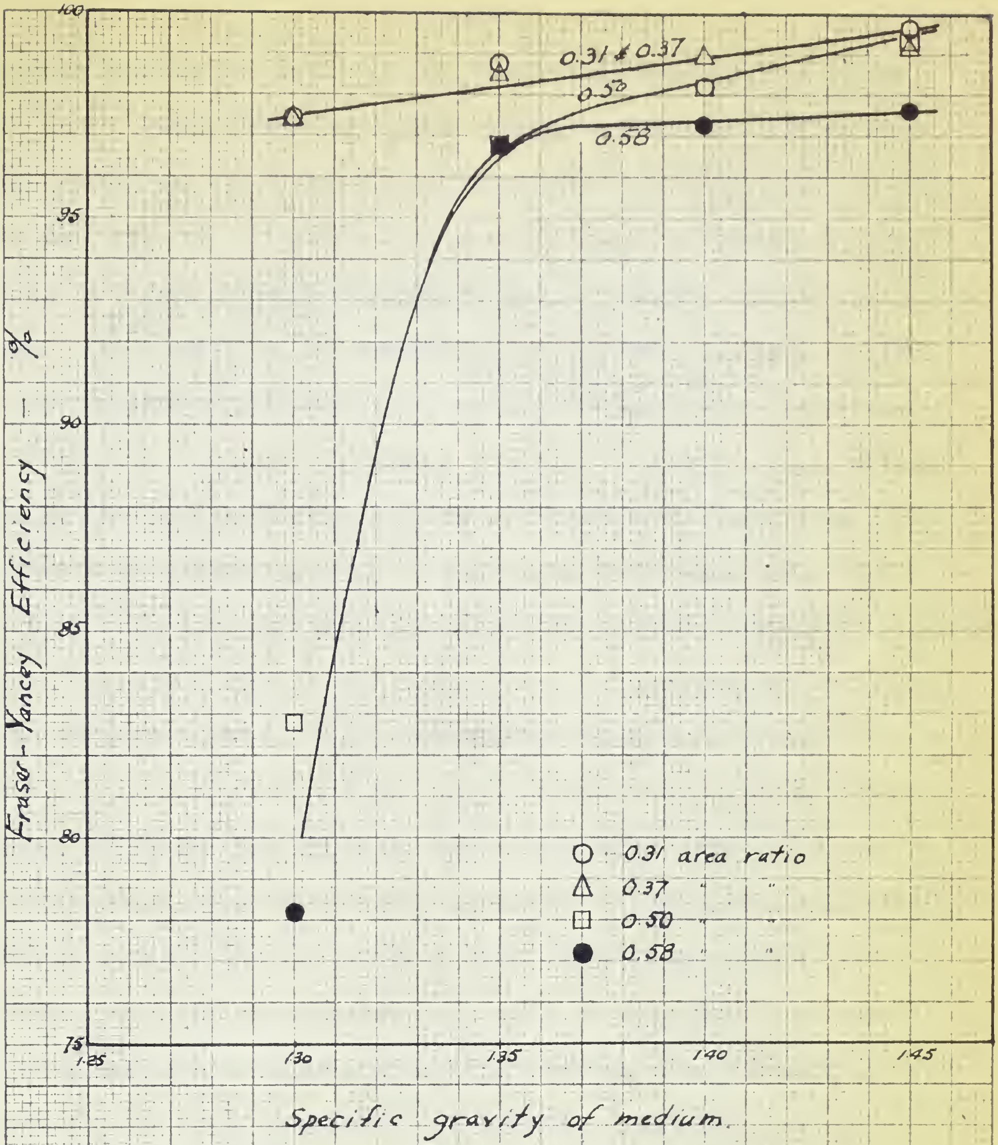

Fig. 28 Curves showing variation in Fraser-Yancey Efficiency for constant cyclone dimensions as specific gravity of medium is varied.

1.65 to 1.80 for the 0.31 and 0.37 size ratios respectively. Under the same conditions the error area rises from 49 to 62 and from 58 to 61. Therefore, the Fraser-Yancey Efficiency displays a trend opposite to that exhibited by the Error Area as the specific gravity of separation is raised by employing higher specific gravities of medium; i.e. under these conditions the Fraser-Yancey Efficiency increases whilst the separation efficiency, as measured by the Error Area, decreases. For both the 0.50 and 0.58 cyclone underflow to overflow area ratios, the Fraser-Yancey efficiencies show an improvement, rising from 80 to 98% when the specific gravity of separation is increased from 1.48 to 1.70 and from 1.42 to 1.64 respectively, by utilizing suspension specific gravities from 1.30 to 1.45. Under identical circumstances the error area decreases from 41 to 38, denoting an improvement in separation efficiency. Therefore, for the larger underflow openings the Fraser-Yancey Efficiency and the Error Area show similar trends when the specific gravity of separation is increased by varying the specific gravity of the medium from 1.30 to 1.45. Thus, the cross-plots of Fraser-Yancey efficiency versus the ratios of underflow to overflow opening area and specific gravity of the medium, when compared with those for the Error Area, show that there is no evident similarity between these two methods of judging coal-cleaning efficiency. Each may vary in a different manner depending on the cyclone dimensions and suspension specific gravity employed.

It will be noted that the only Fraser-Yancey efficiencies which were less than 95% were given by the two largest ratios of underflow to overflow-opening area of 0.50 and 0.58 in combination

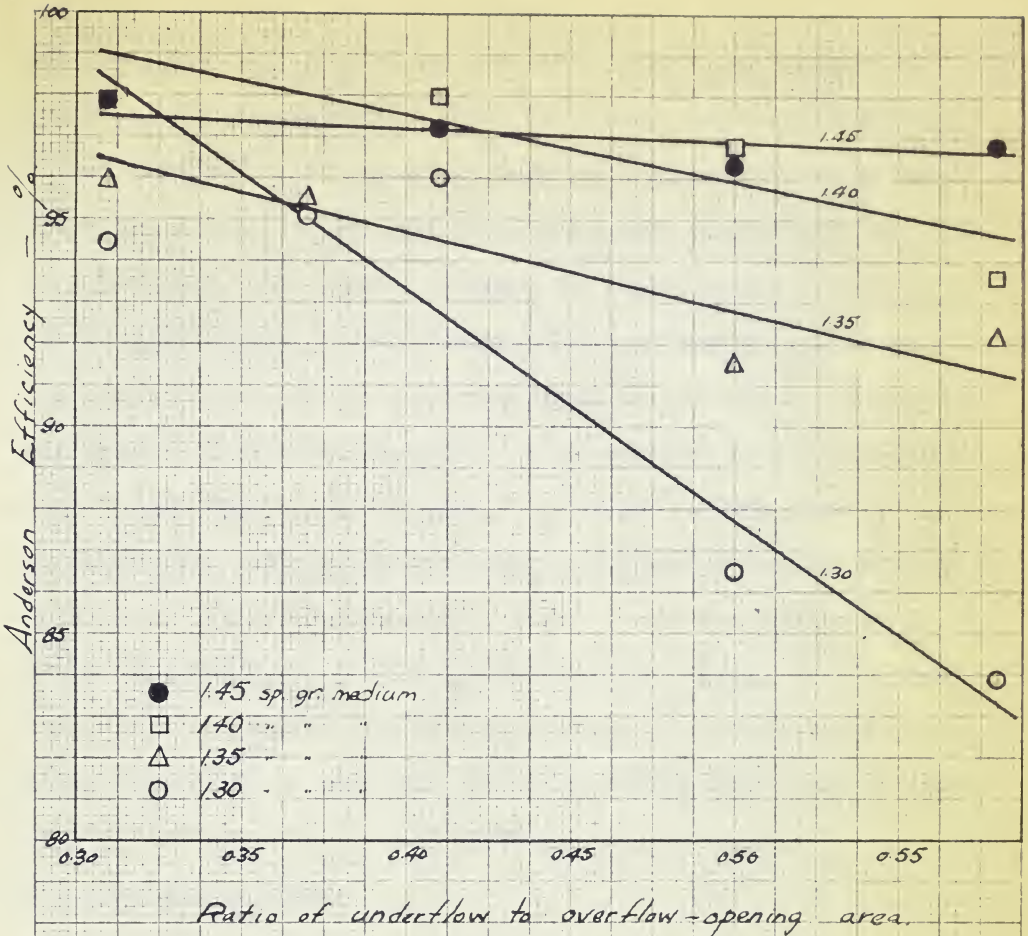

Fig. 29 Curves showing variation in Anderson Efficiency for cyclone operation with constant suspension specific gravities as ratio of underflow to overflow - opening area of cyclone is varied.

with the lightest suspension of 1.30 specific gravity. (Experiment Nos. 58 and 54 respectively). These low Fraser-Yancey efficiencies of 82.8 and 78.1% resulted, even though the error areas were 39 and 41 and the probable errors were 0.066 and 0.064, respectively, for the two separations. The yields for these two separations were low, 53.6 and 54% respectively, as were the specific gravities of separation, 1.40 and 1.41 respectively. For washing in this range, the amount of coal within ± 0.10 specific gravity of the specific gravity of separation in the feed is very high--47.0 and 47.3%* for the feeds of these two experiments. The low Fraser-Yancey efficiencies are probably due to the small yields of washed coal rather than to the difficulty of washing as shown by the ± 0.10 specific gravity values. It is likely that even if the separations were much sharper the Fraser-Yancey efficiencies would still be less than 95% if the washing were performed with such low yields and low specific gravities of separation.

(5) ANDERSON EFFICIENCY

Figs. 29 and 30 represent a cross-plot of the data for the Anderson Efficiency similar to those for the Error Area, Probable Error and Yancey Efficiency in the previous subsections. In Fig. 29 the Anderson efficiencies are plotted versus the ratios of cyclone underflow to overflow area with the specific gravities of the medium as parameters, whereas in Fig. 30 the Anderson efficiencies are plotted against the specific gravities of medium with the area ratios as parameters. These two figures illustrate that the Anderson Efficiency

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*The reason for the ± 0.10 specific gravity values being so great is due to the fact that most of the material in the feed coal has a specific gravity near 1.4.

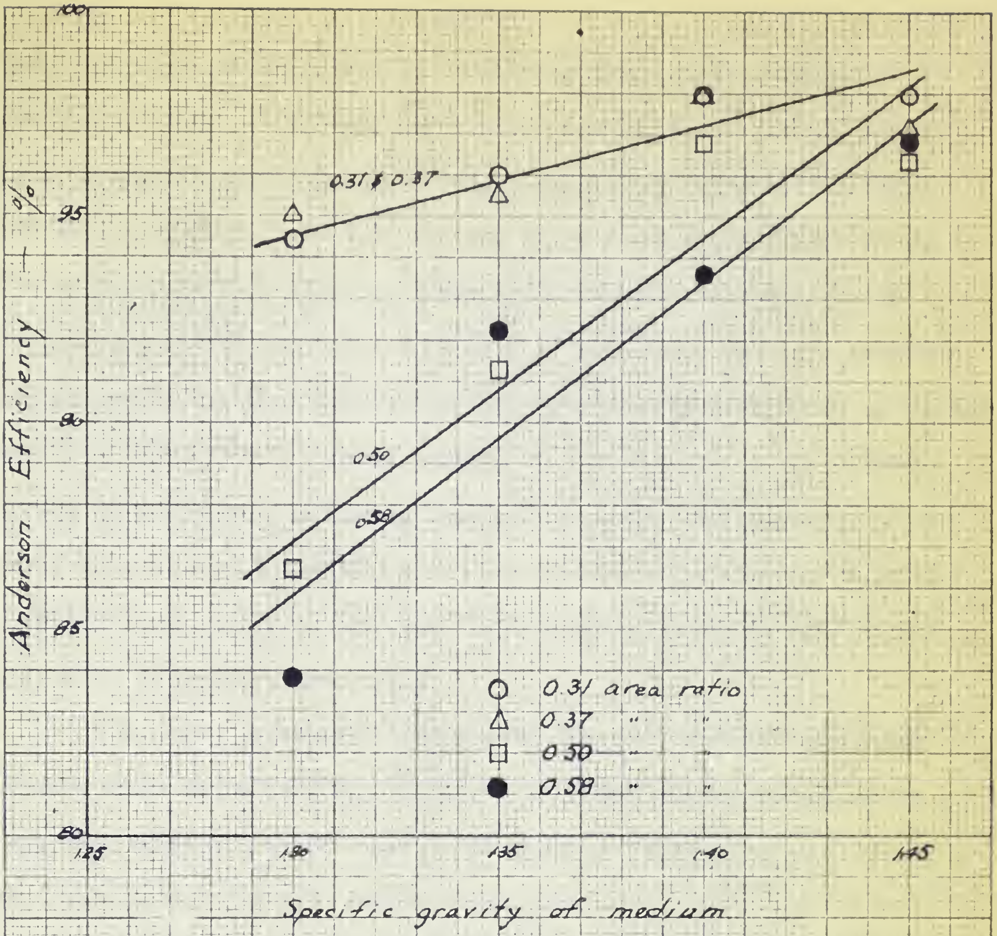

Fig. 30 Cyclone data illustrating variation in Anderson Efficiency for constant cyclone dimensions as the specific gravity of the medium is varied.

shows similar tendencies to those displayed by the Fraser-Yancey Efficiency. Thus in Fig. 29, for the three suspensions of 1.45, 1.40 and 1.35 specific gravity, the Anderson Efficiency increases slightly from 97.0 to 97.5%, 94.5 to 99.0%, and 91 to 96.5% respectively as the size of the underflow opening is decreased so that the underflow to overflow area ratio decreases from 0.58 to 0.31. For the 1.30 specific gravity medium the rise in Anderson Efficiency is much sharper, increasing from 83 to 98% under the above conditions. In Fig. 30 as the specific gravity of the medium is raised from 1.30 to 1.45, the Anderson efficiencies rise from 94.5 to 99.4% for the 0.31 and 0.37 ratios of underflow to overflow-opening area, and from 97.2 to 98.2% and 86 to 97% for the 0.50 and 0.58 ratios respectively.

The only separations which gave Anderson efficiencies below 90% were those which gave the unacceptable Fraser-Yancey efficiencies which were mentioned in the previous subsection (Experiment No. 58 and 54). The large amounts of misplaced material, 13.5 and 16.1% respectively for these two separations are due to the large amounts of material in the feed near the specific gravities of separation (1.40 and 1.41).

(6) RECAPITULATION AND DISCUSSION

In the foregoing subsections it has been demonstrated that the specific gravity of separation is a dependent variable as are the various functions employed in expressing coal-cleaning efficiency. It has been pointed out that the manner in which the specific gravity of separation changes depends upon the variables that are altered to produce this change; in the case of the cyclone these variables are the specific gravity of the medium and size of the underflow-openings providing that

all other variables are held constant. The data presented also reveal that the manner in which the Error Area, Probable Error, Fraser-Yancey Efficiency and Anderson Efficiency vary as the specific gravity of separation is increased depends upon whether the change in specific gravity of separation is achieved by varying the size of the underflow opening or by altering the specific gravity of the medium. Therefore, the variations in the Error Area, Probable Error, Fraser-Yancey Efficiency and Anderson Efficiency must be represented in terms of these two variables rather than the specific gravity of separation which is not an independent variable. The reason for the disagreement among the various coal-preparation authorities as to whether or not the Probable Error and Error Area vary with specific gravity of separation thus becomes quite evident, i.e. they have been attempting to define one dependent variable (Error Area or Probable Error) in terms of another dependent variable (specific gravity of separation). It has been demonstrated that the Fraser-Yancey and Anderson efficiencies increase as the specific gravity of separation is raised but that the variation in these efficiencies is again dependent upon the two variables of cyclone dimensions and specific gravity of the medium. Since the Error Area and Probable Error sometimes display a decrease in separation efficiency with higher specific gravities of separation, it is easy to see why there is often no agreement between the various efficiencies, if, for example, some adjustment is made to the cleaning equipment and the change in the quality of cleaning is calculated by the various methods. It has been pointed out that the Probable Error is an approximation of the Error Area and that this, therefore, probably accounts for the dissimilar results sometimes exhibited by these two methods of expressing separation efficiency. The dissimilarity between the Error

Area and the Fraser-Yancey Efficiency is due to the fact that the latter is a material balance on coal of a certain ash content whilst the former is a measure of the sharpness of separation.

Yancey and Geer (47) have stated that the Fraser-Yancey Efficiency and sharpness of separation are two entirely different things and therefore cannot be compared. Therefore, they object to the use of the term "efficiency" for those methods which evaluate only sharpness of separation. In view of the data submitted in the present investigation, it is evident that there is no relationship between the Fraser-Yancey Efficiency and the sharpness of separation as shown by the Error Area and Probable Error. It is also true that the Error Area and Probable Error are not actually "efficiencies" in that they are not expressed as percentages. However, this is not the case with the Area Efficiency, which is proposed in this thesis as a measure of the sharpness of separation. Therefore, it is difficult to see any objection to calling the Area Efficiency an efficiency of separation.

The French Cerchar have suggested the use of a function called the "Magnitude of Imperfection" to correct for the higher probable errors which are said to result at higher specific gravities of separation. The "Magnitude of Imperfection" (I), is obtained by dividing the Probable Error ($\mathcal{E}$) by the specific gravity of separation minus one ($d_p - 1$). It is difficult to see the justification for such a modification to the Probable Error, since it has been shown that for washing performed by the cyclone, the Probable Error is not dependent upon the specific gravity of separation alone. The Cerchar investigators have justified the use of the probability scale for transforming

the distribution curves into straight lines on the premise that the reciprocals of the slopes of these transformed curves are approximately equal to the "Magnitude of Imperfection" for separations following the "logarithmic-normal law", whereas the reciprocals of the slopes of the transformed curves for separations following the "normal law" are approximately equal to the probable error. If the Probable Error is not dependent on the specific gravity of separation, the "Magnitude of Imperfection" has no meaning. Therefore, the fact that the reciprocals of the slopes of the transformed curves are equal to this function is of little or no significance. The primary object of the straight-line transformation is to obtain greater accuracy in fixing the specific gravity of separation. It has been made clear that the transformed curves for the cyclone separations in the present investigation did not yield straight lines and that these results coincided with the findings of Yancey and Geer (47). Since these transformed curves often give much less accuracy than the curves plotted in the normal manner, there does not seem to be any valid reason for using special graph paper and various scales on the abscissa in order to procure straight-line distribution curves.

IX CONCLUSIONS

INFLUENCE OF OPERATING VARIABLES

Operation of the cyclone washer can be adequately controlled by regulation of the size of the underflow opening while holding all other variables constant. Suspensions with a specific gravity of 1.30 can be used to perform satisfactory coal-washing at specific gravities ranging from 1.60 to 1.70 with probable errors of approximately 0.07 and error areas varying from 40 to 50.

Improved separation occurs as the pulp ratio is increased from three-to-one to eight-to-one. A large error area of 86 and low Fraser-Yancey efficiency of 93.4% resulted with the three-to-one pulp ratio but satisfactory cleaning can be accomplished with pulp ratios between four-to-one and eight-to-one inclusive. For this range of pulp ratios the error areas varied from 71 to 47 and the Fraser-Yancey efficiencies varied from 97.2 to 98.3%.

Specific gravity composition of the feed has no appreciable effect on the performance of the cyclone washer. Feeds with ± 0.10 specific gravity values between 23.6 and 9.8 were cleaned with resulting error areas between 29 and 46 and Fraser-Yancey efficiencies between 96.1 and 97.5%.

Particle size of the feed coal has a very marked influence on the separation efficiency achieved by the cyclone washer. The washing results become progressively poorer as the particle size decreases. Error Areas were 44 for the 10- to 14-mesh size fraction and 84 for the 65- to 100-mesh fraction. The corresponding Fraser-Yancey efficiencies were 99.9 and 97.8. The specific gravity of separation increases as the particle size decreases; the specific

gravity of separation for the 10- to 14-mesh fraction was 1.63 whereas that for the 65- to 100-mesh fraction was 1.84.

In view of the evidence showing the influence of pulp ratio of the feed slurry, specific gravity composition of the feed, and particle size of the feed on cyclone performance it is evident that the cyclone is able to cope with radical changes in feed quality and feed rate but that the size composition of the feed must not be allowed to vary widely if the quality of the washed-coal product is to be kept within certain limits.

INFLUENCE OF UNDERFLOW OPENING AND SPECIFIC GRAVITY OF MEDIUM ON APPARENT EFFICIENCY OF CLEANING

For washing accomplished by the cyclone, the specific gravity of separation depends upon the variables of size of underflow opening and specific gravity of the medium (providing that all the other variables are fixed). Similarly the Error Area is also dependent on these two variables. The Error Area thus does not depend upon the specific gravity of separation since it may either decrease, remain constant, or increase, as the specific gravity of separation is raised; the manner in which this variation in Error Area occurs depends upon whether the specific gravity of separation is increased by varying the cyclone underflow dimension or by changing the specific gravity of the medium.

The Probable Error, which is an approximation of the Error Area shows results similar to those given by the Error Area. The discrepancy between the two is due to the fact that the Probable Error takes into account only that part of the distribution curve between

25 and 75% of the ordinate, whereas the Error Area takes the whole curve into account.

The Fraser-Yancey and Anderson Efficiencies demonstrate similar trends, showing slightly greater values as the specific gravity of separation is increased by either using lighter specific gravities of suspension or decreasing the size of the underflow opening.

The Error Area and Probable Error do not show similar results as the Fraser-Yancey Efficiency because the latter is actually a material balance on coal of a certain ash content, whereas the two first-named methods show the sharpness of separation according to specific gravity of the feed coal.

Satisfactory cleaning results when the probable errors are greater than 0.07 although this figure was thought by Cerchar investigators to be much too high for satisfactory coal-washing.

The method of transformation of the distribution curves proposed by Cerchar investigators was not applicable to the cyclone separations accomplished in this investigation. No justification is seen for the "Magnitude of Imperfection" proposed by Cerchar investigators since the Probable Error does not depend upon the specific gravity of separation alone.

A new method of expressing the separation efficiency of coal-cleaning equipment is proposed. This method is based upon the Error Area and expresses the Error Area as a percentage efficiency rather than as an area in square centimeters.

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